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Beta decays and non-standard interactions in the LHC era

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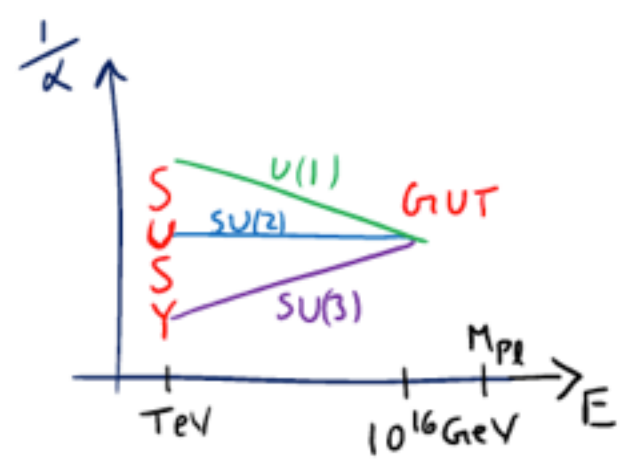
Introduction

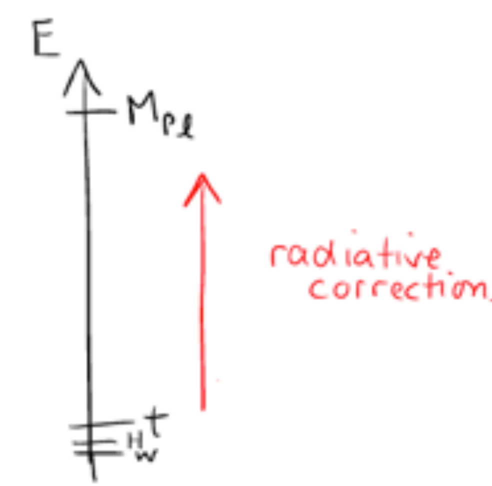
Why “beyond the Standard Model”?

- The SM is remarkably successful, but has no answer to a number of questions about our universe $\Rightarrow$ new degrees of freedom

Empirical questions

Theoretical questions

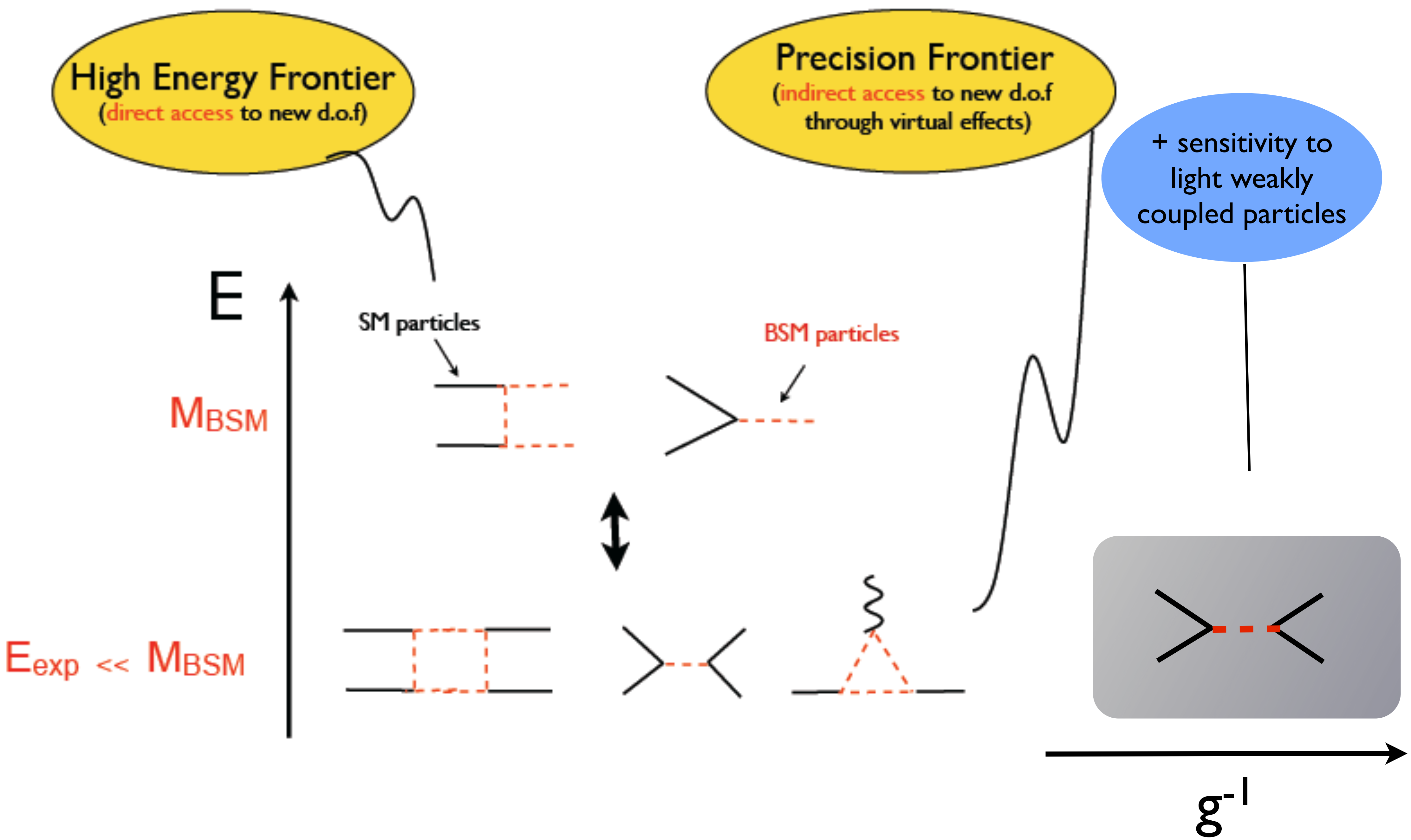




R. Sundrum
ICHEP 12

Two Frontiers

- Two *complementary* strategies to probe BSM physics:



Two Frontiers

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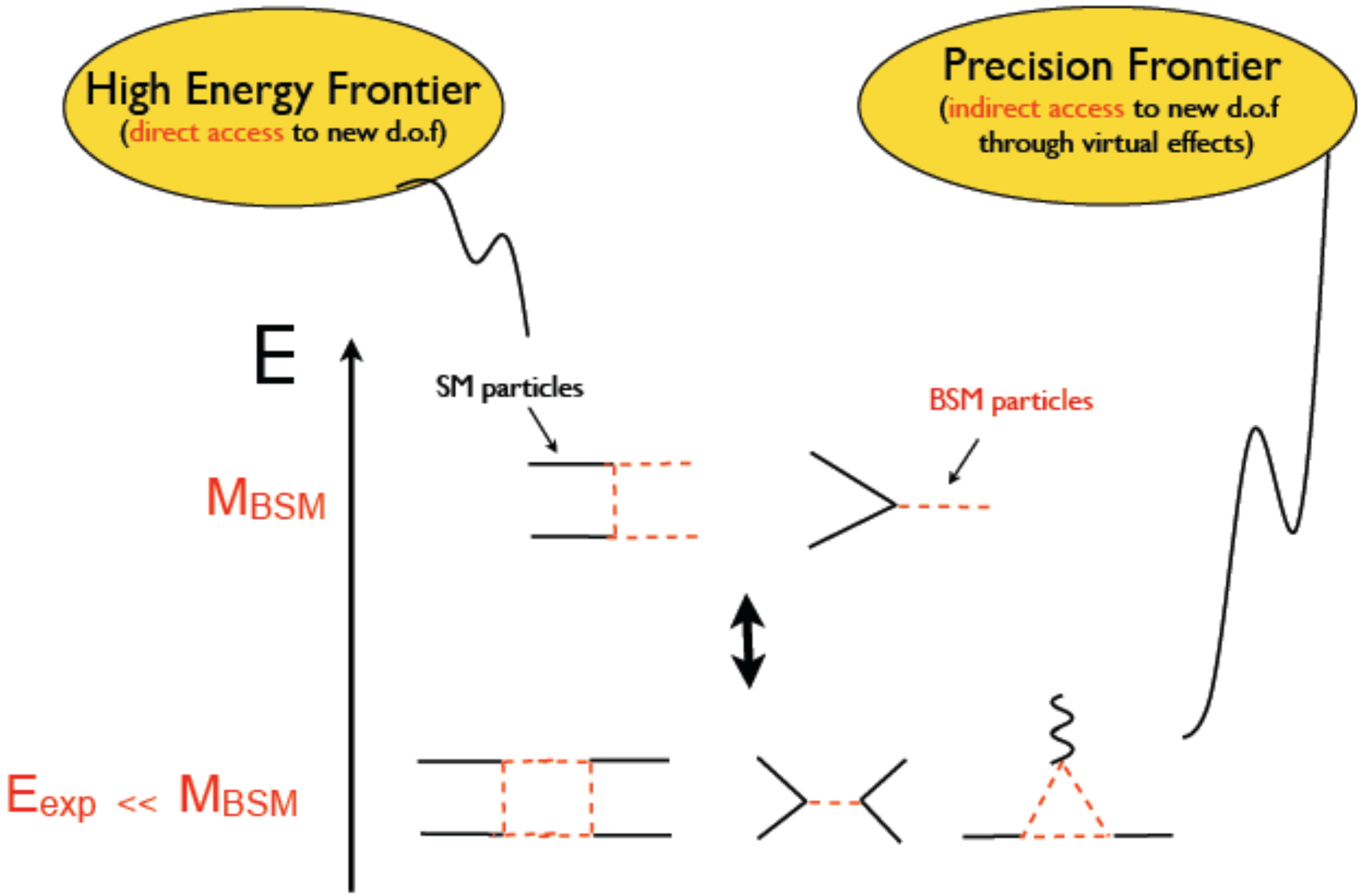
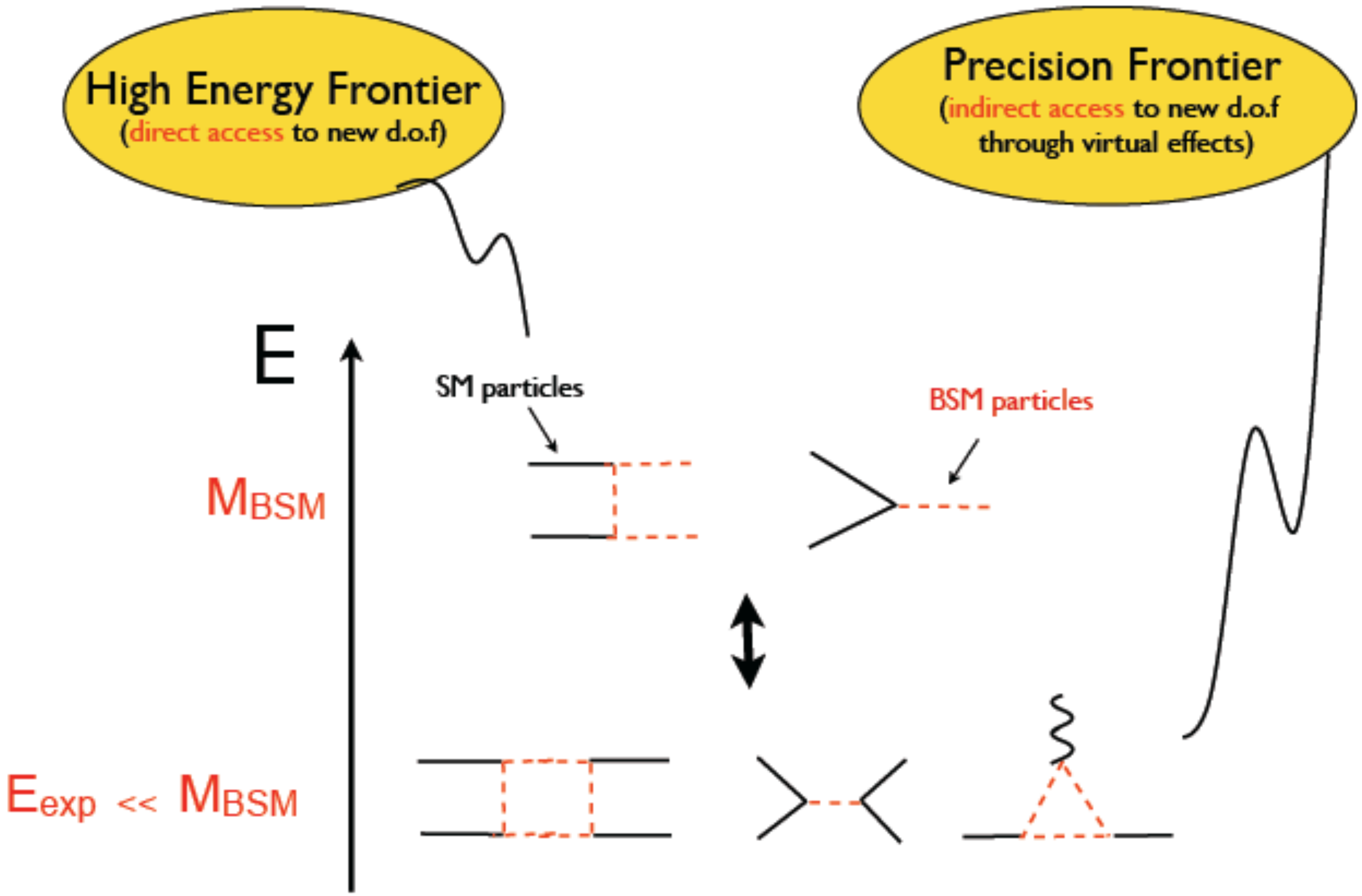


- Both frontiers needed to reconstruct the structure, symmetries, and parameters of $\mathcal{L}_{BSM}$ $\Rightarrow$ address the outstanding open questions

Two Frontiers

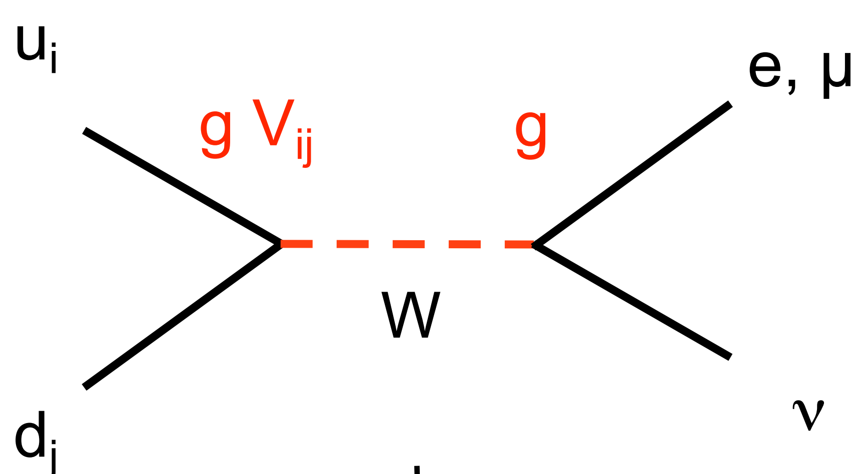
- Two *complementary* strategies to probe BSM physics:



- In this talk, take a fresh look at non-standard charged current interactions, using both Precision and Energy Frontier probes

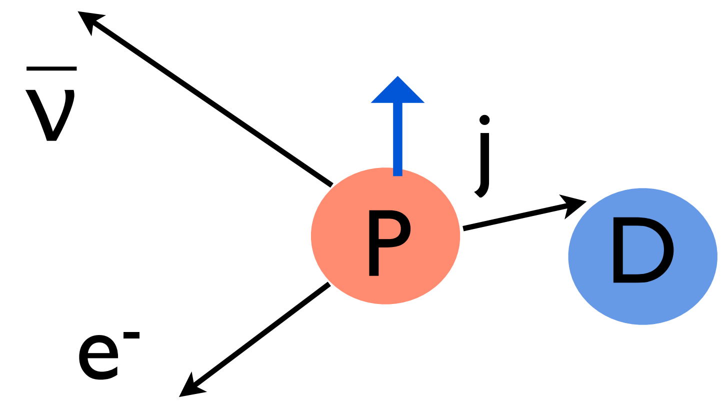
CC interactions and BSM physics

- In the SM, W exchange ⇒ only V-A structure, universality relations



at low energy

$G_F \sim g^2 V_{ij}/M_W^2 \sim 1/v^2$



Peculiar "V-A" pattern in spectra and decay correlations

Lepton universality

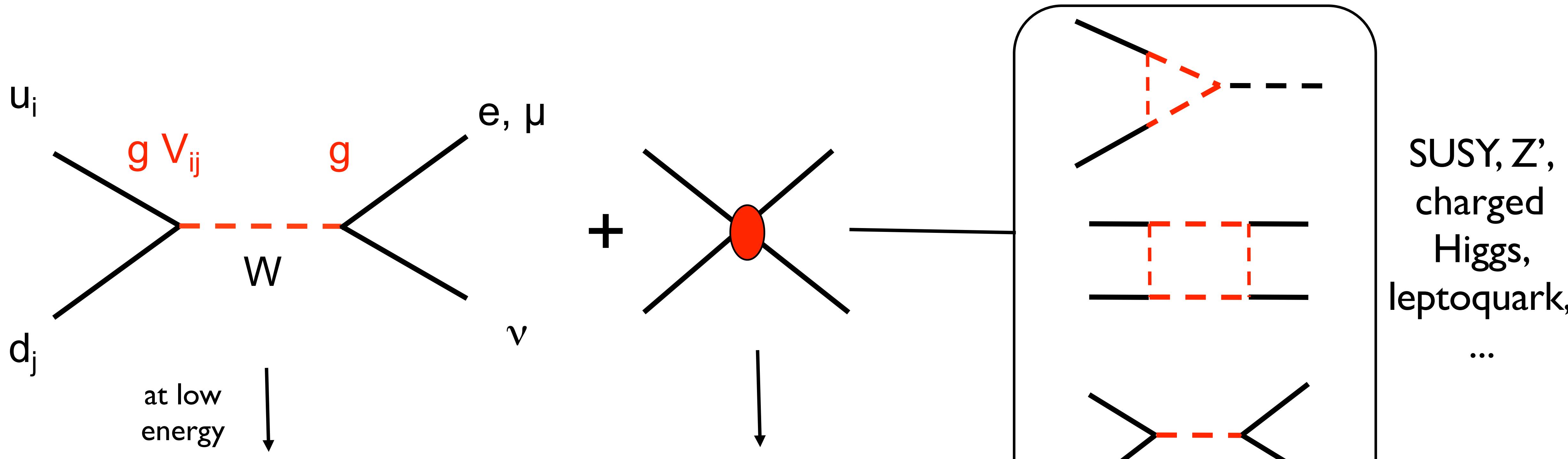
$$[G_F]_e/[G_F]_\mu = 1 + \Delta_{e/\mu}$$

$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 1 + \Delta_{\rm CKM}$$

Cabibbo universality

CC interactions and BSM physics

- In the SM, W exchange ⇒ only V-A structure, universality relations

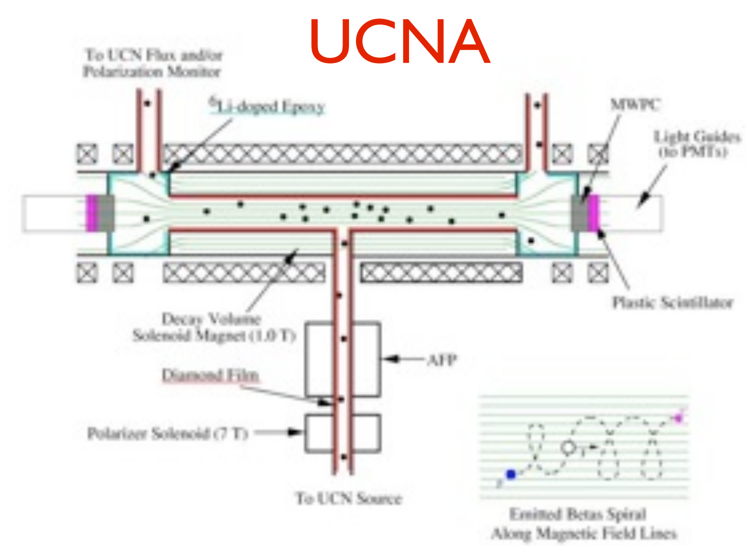


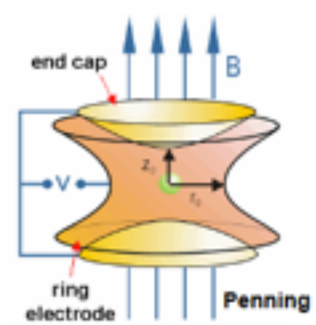
$G_F \sim g^2 V_{ij}/M_W^2 \sim 1/v^2$

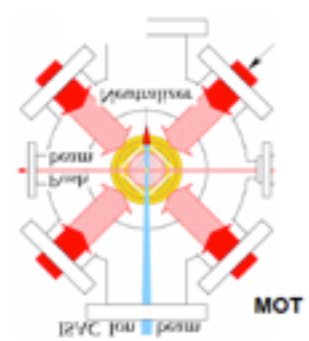
$1/\Lambda^2$

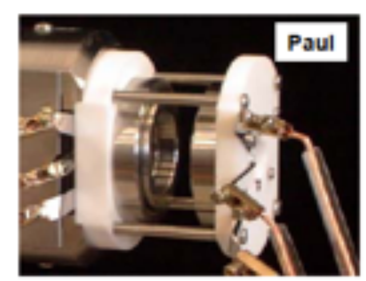
- BSM: sensitive to tree-level and loop corrections from large class of models → "broad band" probe of new physics

- Traditionally, field dominated by precision β decay measurements: rich experimental program worldwide, with precision approaching the 0.1%-level or better

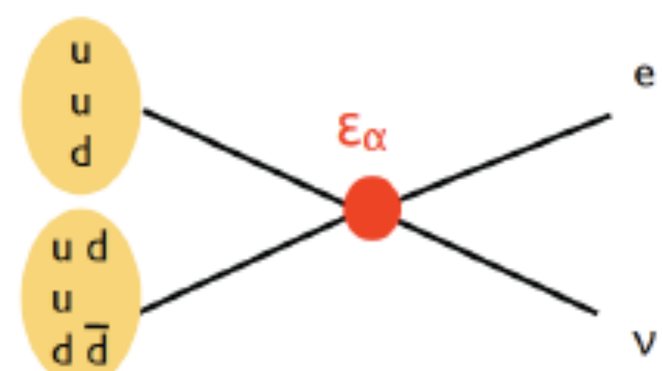








- Here consider multi-scale analysis, with probes ranging from low energy (nuclei, neutron, and pion) to the LHC



Outline

- EFT approach to Charged Current interactions

- Beta-decay probes (Precision Frontier)

- Collider probes (Energy Frontier)

1) T. Bhattacharya, VC, S.Cohen, A Filipuzzi, M. Gonzalez-Alonso, M. Graesser, R. Gupta, H.W.Lin, arXiv:1110.6448 [hep-ph], PR D85 (2012) 054512
2) VC, M. Gonzalez-Alonso, M. Graesser, arXiv:1205.2695, JHEP 1210 (2012) 025
3) V. Cirigliano, S. Gardner, B. R. Holstein, arXiv:1303.6953, Prog.Part.Nucl.Phys. 71 (2013) 93-118
4) VC, ,M. Graesser, E. Passemar, in progress

* Precision Neutron Decay Matrix Elements (PNDME) lattice QCD collaboration

Framework

Theoretical Framework

- In absence of an emerging BSM scenario, work within EFT framework
    - Assume separation of scales $M_{BSM} >> M_W$
    - New heavy BSM particles are "integrated out" and affect low-energy dynamics through local operators of dim > 4
    - If M_{BSM} ~ several TeV, one can use this framework to analyze LHC data. Will discuss relaxing this assumption at the end of the talk
- EFT approach can be used to put constraints on *any* UV model
- EFT approach misses possible correlations among observables

Theoretical Framework

E

LHC

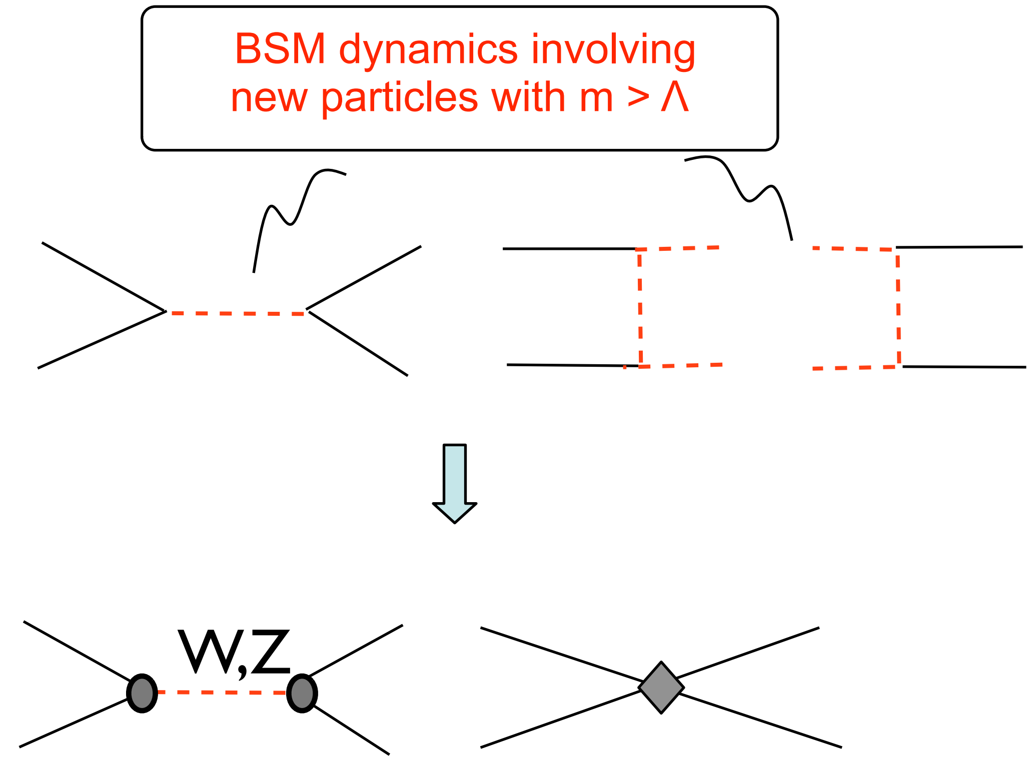
Λ (~TeV)

SLC, LEP

$M_{W,Z}$

LANSCE, SNS, ...

Λ_H (~GeV)



$$\mathcal{L}_{\rm BSM}$$

$$\mathcal{L}_{\rm SM} + \sum_i \frac{O_i}{\Lambda_i^2} + \ldots$$

12 SU(2)xU(1) gauge invariant operators O_i affect CC interactions

Theoretical Framework

LHC

SLC, LEP

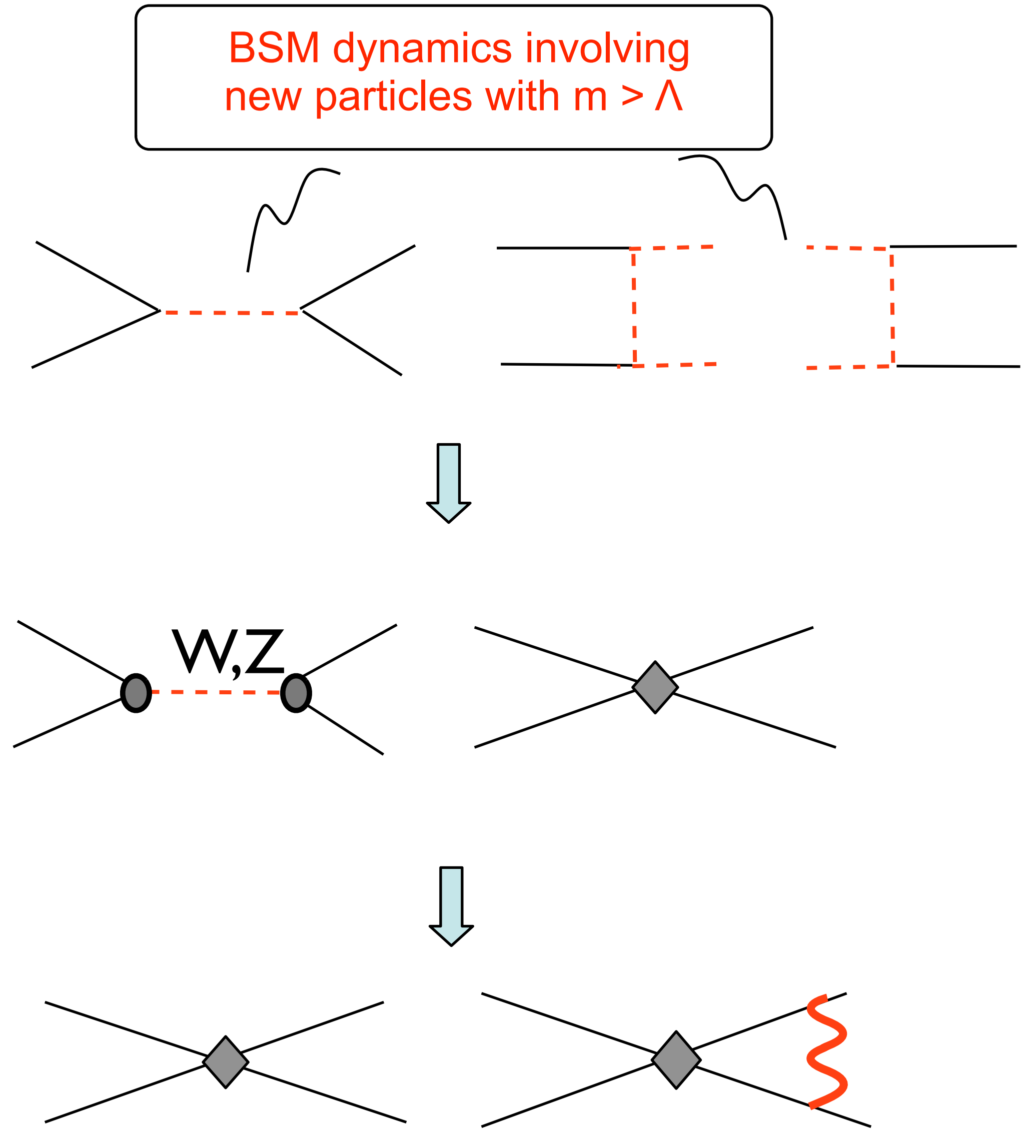
LANSCE, SNS, ...

E

Λ (~TeV)

$M_{W,Z}$

Λ_H (~GeV)



$$\mathcal{L}_{\rm BSM}$$

$$\mathcal{L}_{\rm SM} + \sum_i \frac{O_i}{\Lambda_i^2} + \dots$$

$$\mathcal{L}_{\rm Fermi} + \mathcal{L}_{\rm QCD} + \mathcal{L}_{\rm QED}$$

$$-\frac{G_F V_{ud}}{\sqrt{2}} \sum_\Gamma \epsilon_\Gamma \, \bar{\ell}\Gamma\nu \cdot \bar{u}\Gamma d$$

10 4-fermion operators

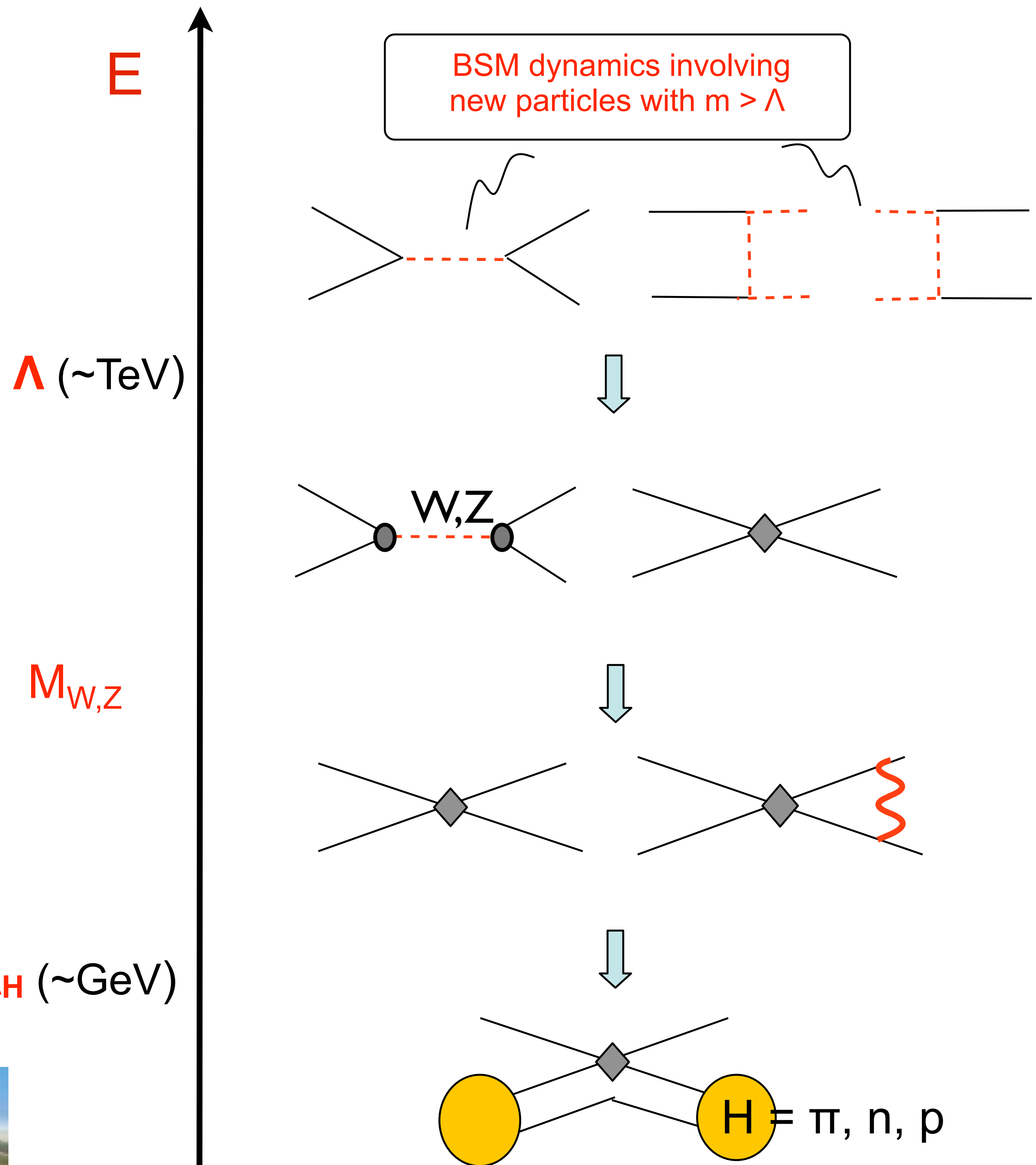
$$\epsilon_\Gamma = \sum_i c_{\Gamma i} \frac{v^2}{\Lambda_i^2}$$

Theoretical Framework

LHC

SLC, LEP

LANSCE, SNS, ...



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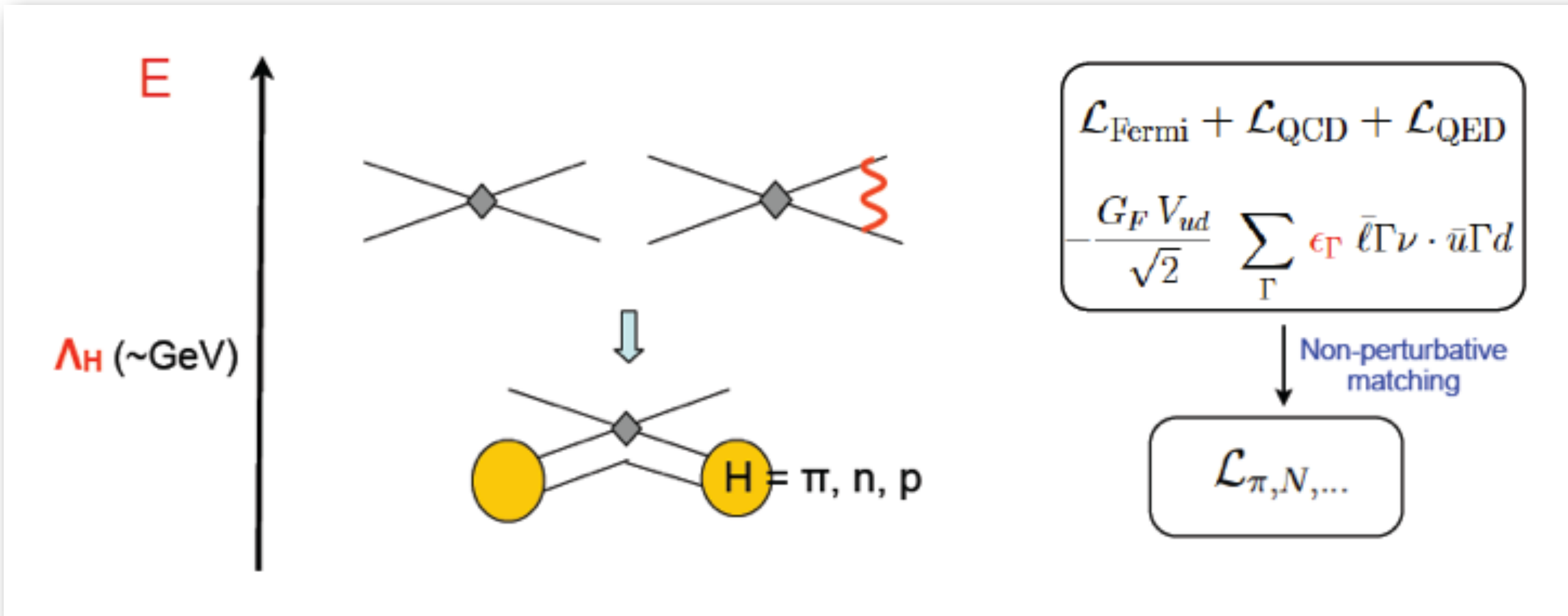
$$-\frac{G_F\, V_{ud}}{\sqrt{2}} \sum_\Gamma \epsilon_\Gamma\, \bar{\ell}\Gamma\nu \cdot \bar{u}\Gamma d$$

Non-perturbative matching

$$\mathcal{L}_{\pi, N, \ldots}$$

Match to hadronic description (1)



- To disentangle short-distance physics, need hadronic matrix elements of SM (very precisely, 10^{-3} level) *and* BSM operators
- Tools:
  - symmetries of QCD (→ chiral EFT)
  - lattice QCD

Match to hadronic description (2)

- Need the matrix elements of quark bilinears between nucleons

$$\langle p(p_p, s')|\ \bar{u}\,\Gamma\, d\ |n(p_n, s)\rangle = \bar{u}(p_p, s')\ f_\Gamma(q^2)\ u(p_n, s)$$

- Given the small momentum transfer in the decays $q/m_n \sim 10^{-3}$, can organize matching according to power counting in q/m_n

- At what order do we stop? Work to 1st order in

$$\epsilon_\Gamma \sim 10^{-3} \qquad q/m_n \sim 10^{-3} \qquad \alpha/\pi \sim 10^{-3}$$

- Include $O(q/m_n)$ and rad. corr. only for SM operator

- Caveat: this counting neglects "2nd class currents" effects, $O(10^{-5} \sim q/m_n \times \text{isospin-breaking})$ [Gardner-Plaster arXiv:1305.0014 discuss impact of these effects]

Low-energy probes

Low-scale Lagrangian

$\epsilon_i \sim (v/\Lambda)^2$

$$\mathcal{L}_{\rm CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \times \Big[(1+\delta_{RC}+\epsilon_L)\;\bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d$$

$$+\;\epsilon_R\;\bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d$$

$$+\;\epsilon_S\;\bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}d$$

$$-\;\epsilon_P\;\bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d$$

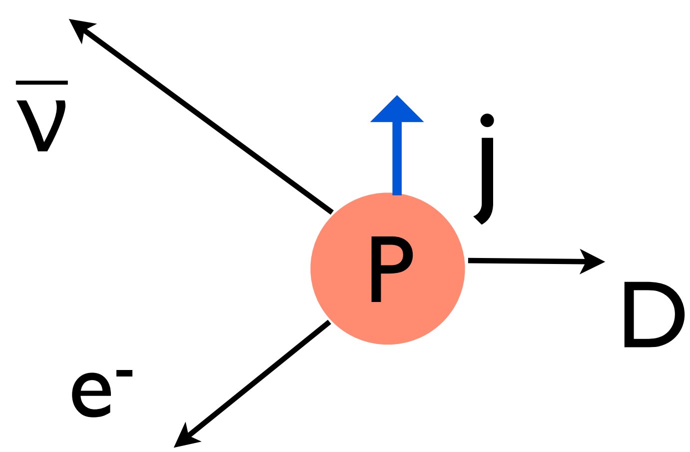
$$+\;\epsilon_T\;\bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d\,\Big] + \text{h.c.}$$

$$+\quad \epsilon_i \longrightarrow \tilde{\epsilon}_i \qquad (1-\gamma_5)\nu_\ell \longrightarrow (1+\gamma_5)\nu_\ell$$

How do we probe the ε's?

- Low-energy probes fall roughly in two classes:

I. Differential decay rates: spectra, angular correlations (mostly non V-A)



Jackson-Treiman-Wyld 1957

$$d\Gamma \propto F(E_e)\left\{1 + b\,\frac{m_e}{E_e} + a\,\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + \langle\vec{J}\rangle\cdot\left[\,A\,\frac{\vec{p}_e}{E_e} + B\,\frac{\vec{p}_\nu}{E_\nu} + \cdots\right]\right\}$$

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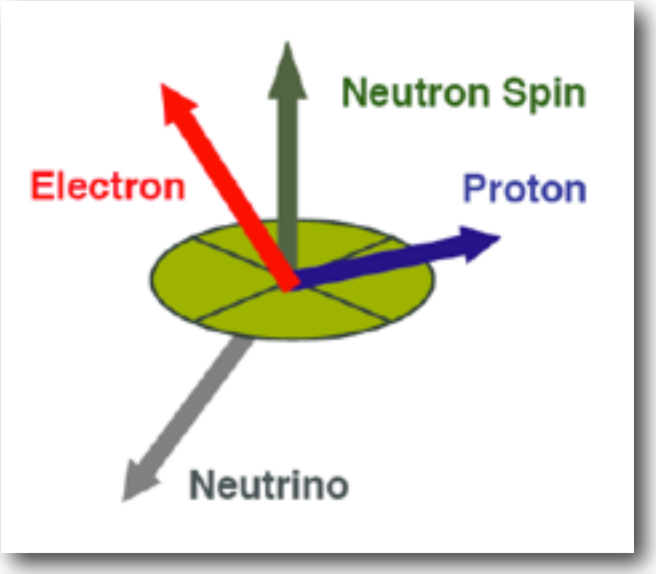

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$$d\Gamma \propto F(E_e) \left\{ 1 + b\,\frac{m_e}{E_e} + a\,\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \langle \vec{J} \rangle \cdot \left[A\,\frac{\vec{p}_e}{E_e} + B\,\frac{\vec{p}_\nu}{E_\nu} + \cdots \right] \right\}$$

$a(\varepsilon_\alpha)$, $A(\varepsilon_\alpha)$, $B(\varepsilon_\alpha)$ isolated via suitable experimental asymmetries

How do we probe the ε's?

- Low-energy probes fall roughly in two classes:

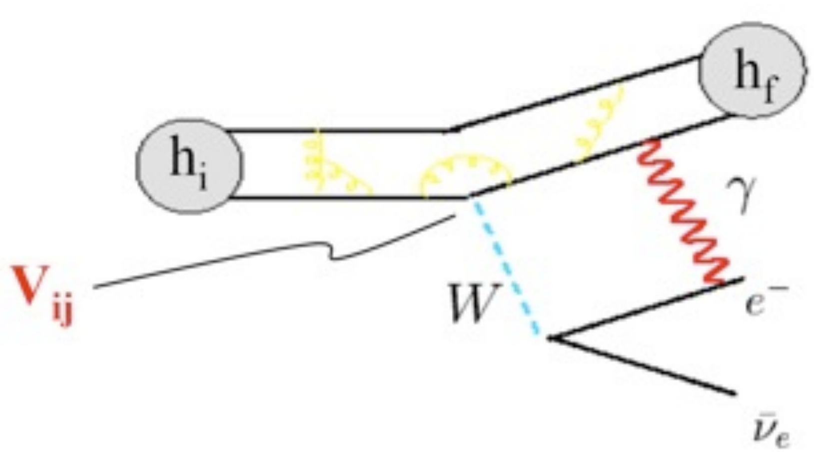
2. Total decay rates: normalization (mostly V, A) matters!

$$\Gamma_k = (G_F^{(\mu)})^2 \times |\bar{V}_{ij}|^2 \times |M_{\rm had}|^2 \times (1 + \delta_{RC}) \times F_{\rm kin}$$

Channel-dependent effective CKM element:

Hadronic matrix element

Radiative corrections (both SD and LD)



$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + |\bar{V}_{ub}|^2 = 1 + \Delta_{\rm CKM}(\epsilon_i)$$

Survey of constraints

$$\begin{aligned}
\mathcal{L}_{\rm CC} &= -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \left(1 + \delta_{RC} + \epsilon_L + \epsilon_R\right) \\
&\times \Big[\bar{\ell}\gamma_\mu (1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu \Big(1 - (1 - 2\,\epsilon_R)\,\gamma_5\Big) d \\
&+ \epsilon_S \;\; \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u} d \\
&- \epsilon_P \;\; \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d \\
&+ \epsilon_T \;\; \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5) d \Big] + \text{h.c.}
\end{aligned}$$

$$+ \quad \epsilon_i \longrightarrow \tilde{\epsilon}_i \qquad (1-\gamma_5)\nu_\ell \longrightarrow (1+\gamma_5)\nu_\ell$$

Survey of constraints

$$\mathcal{L}_{\mathrm{CC}} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} (1 + \delta_{RC} + \epsilon_L + \epsilon_R)$$

- "No interference" between SM amplitude and $\tilde{\epsilon}_i$ couplings (m_ν/E_ν)
- Spectra and angular correlations probe $\tilde{\epsilon}_i$ to *quadratic order*
- Generally weaker bounds (5-10% level)

$$- \quad \epsilon_P \quad \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d$$

$$+ \quad \epsilon_T \quad \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \Big] + \mathrm{h.c.}$$

$$+ \qquad \epsilon_i \longrightarrow \tilde{\epsilon}_i \qquad (1-\gamma_5)\nu_\ell \longrightarrow (1+\gamma_5)\nu_\ell$$

Survey of constraints

$$\mathcal{L}_{CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \left(1 + \delta_{RC} + \epsilon_L + \epsilon_R\right)$$

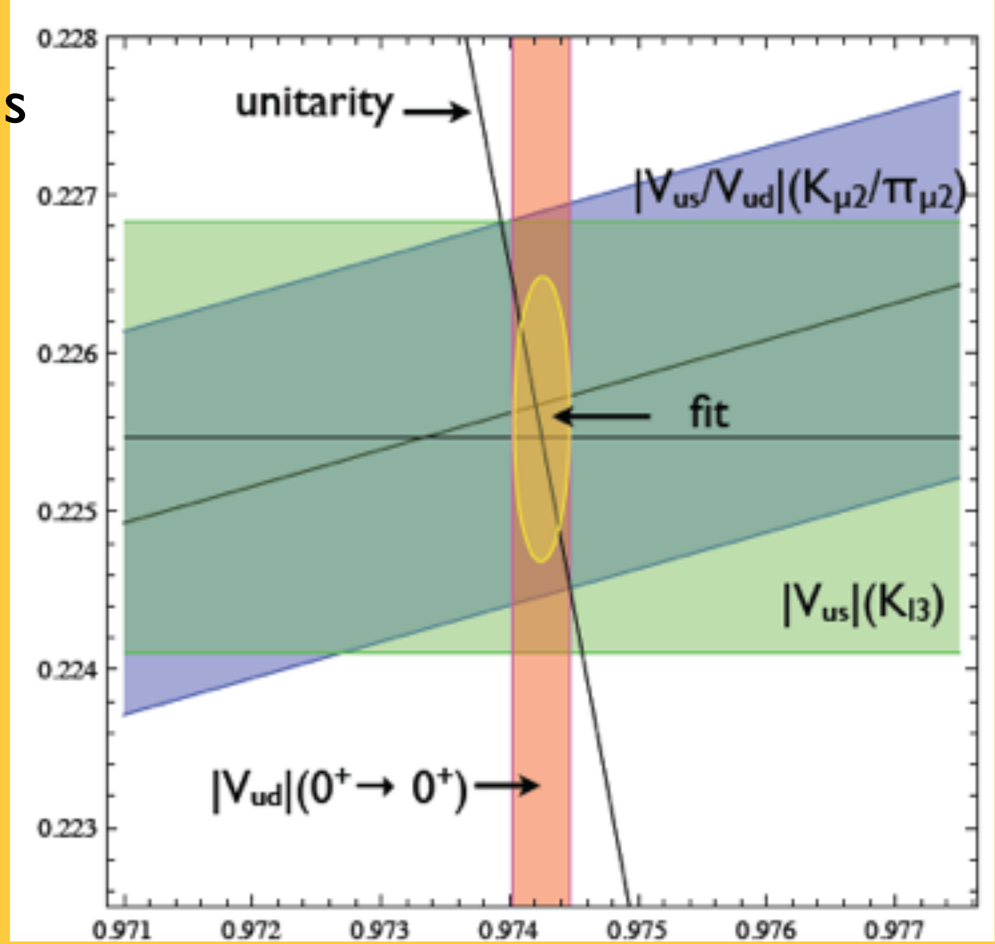
- Affects overall normalization of "semi-leptonic" G_F
- Strong constraints from Cabibbo universality tests,

$\Delta_{CKM} = (1 \pm 6) * 10^{-4}$

$\epsilon_L + \epsilon_R < 5 * 10^{-4}$ @ 90% CL

$\Lambda > 11$ TeV

V_{us}



V_{ud}

Survey of constraints

$$\mathcal{L}_{\rm CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} (1 + \delta_{RC} + \epsilon_L + \epsilon_R)$$

$$\times \Big[\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu \Big(1 - (1 - 2\,\epsilon_R)\,\gamma_5\Big) d$$

$$+ \ \epsilon_S \ \bar{\ell}(\ldots$$

$$- \ \epsilon_P \ \bar{\ell}(\ldots$$

$$+ \ \epsilon_T \ \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5) d \Big] + \text{h.c.}$$

- Affects relative normalization of axial and vector currents
- Neutron and nuclear decays sensitive to $(1\text{-}2\varepsilon_R)*g_A$
- Disentangling ε_R requires precision lattice calculations of g_A: we are not there (yet)

Survey of constraints

$$\mathcal{L}_{CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} (1 + \delta_{RC} + \epsilon_L + \epsilon_R)$$

$\times \Big[\bar{\ell}\gamma_\mu$ ...

$+ \; \epsilon_S \; \bar{\ell}$ ...

$- \; \epsilon_P \; \bar{\ell}$ ...

$+ \; \epsilon_T \; \bar{\ell}$ ...

- Strong constraints from $R_\pi = \Gamma(\pi \to e\nu) / \Gamma(\pi \to \mu\nu)$ (depend on the structure of $(\varepsilon_P)^{ab}$ in lepton flavor space)

$$\Delta_{e/\mu} = (R_\pi)/(R_\pi)_{SM} - 1 = (-3 \pm 3) * 10^{-3}$$

$|\varepsilon_L - \varepsilon_R| < 2.5 * 10^{-3}$ $\quad \Lambda_{L-R} > 3.5$ TeV

$|\varepsilon_P| < 6 * 10^{-4}$ $\quad \Lambda_P > 7$ TeV

@ 90% CL

Survey of constraints

- Neutron and nuclear decay correlation coefficients and spectra
- π → e ν γ Dalitz plot (tensor coupling)

$$\mathcal{L}_{\rm CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{\ldots}} \ldots$$

$$\times \left[\bar{\ell}\gamma_\mu(\ldots \right.$$

$$+ \epsilon_S \; \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}d$$

$$- \epsilon_P \; \bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d$$

$$\left. + \epsilon_T \; \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \right] + \text{h.c.}$$

Constraints on $\varepsilon_{S,T}$

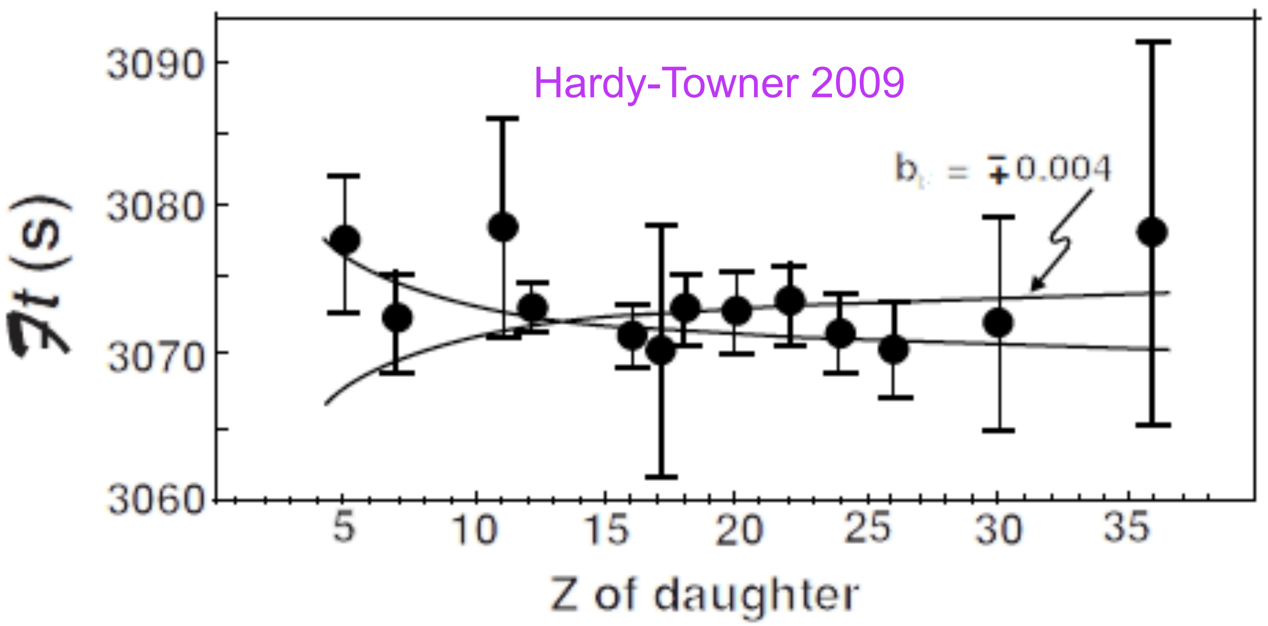
- Only $\varepsilon_{S,T}$ contribute to decay correlations to linear order ε's
  - b and B = B_0 + b_ν m_e/E_e directly sensitive to $\varepsilon_{S,T}$
  - a and A indirectly sensitive to $\varepsilon_{S,T}$ via b in the asymmetry "denominator"

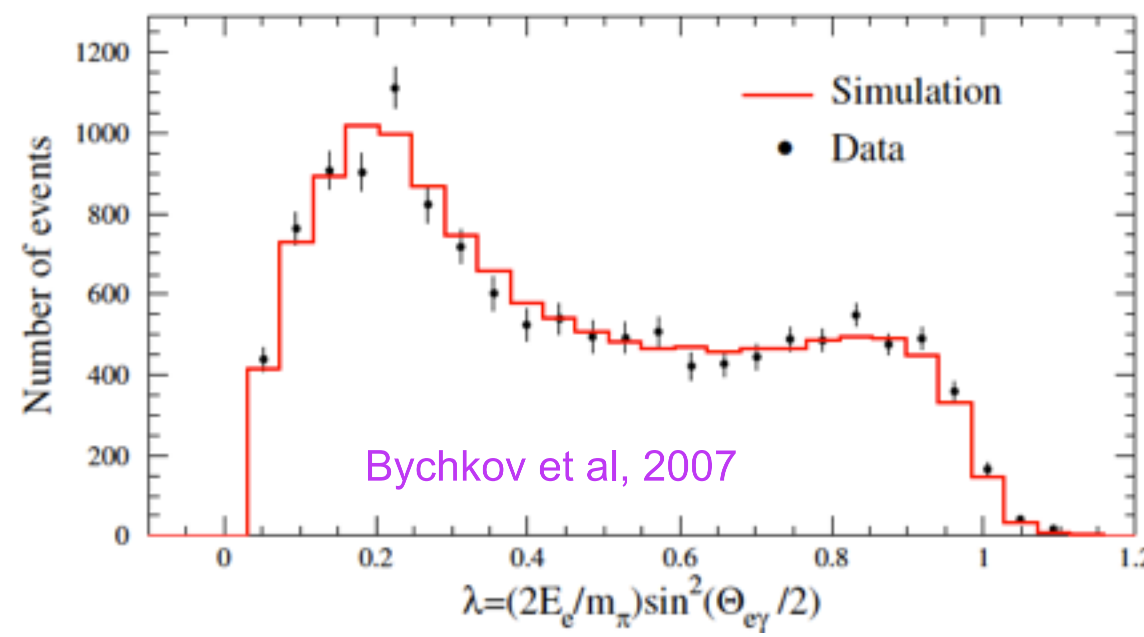
$$\tilde{a} = \frac{a_{SM}}{1 + b\,\langle m_e/E_e\rangle} \qquad \tilde{A} = \frac{A_{SM}}{1 + b\,\langle m_e/E_e\rangle}$$

$$d\Gamma \propto F(E_e)\left\{1 + b\,\frac{m_e}{E_e} + a\,\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + \langle\vec{J}\rangle\cdot\left[\,A\,\frac{\vec{p}_e}{E_e} + B\,\frac{\vec{p}_\nu}{E_\nu} + \cdots\right]\right\}$$

Constraints on $\varepsilon_{S,T}$

- Current: $0^+ \rightarrow 0^+$ (b_F) and $\pi \rightarrow e\,\nu\,\gamma$ and neutron + nuclear decays



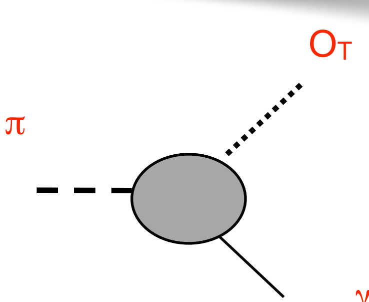


$-1.0\times10^{-3} < g_S\,\varepsilon_S < 3.2\times10^{-3}$

$-2.0\times10^{-4} < f_T\,\varepsilon_T < 2.6\times10^{-4}$

$$b_F = 2\gamma\, g_S\, \epsilon_S$$

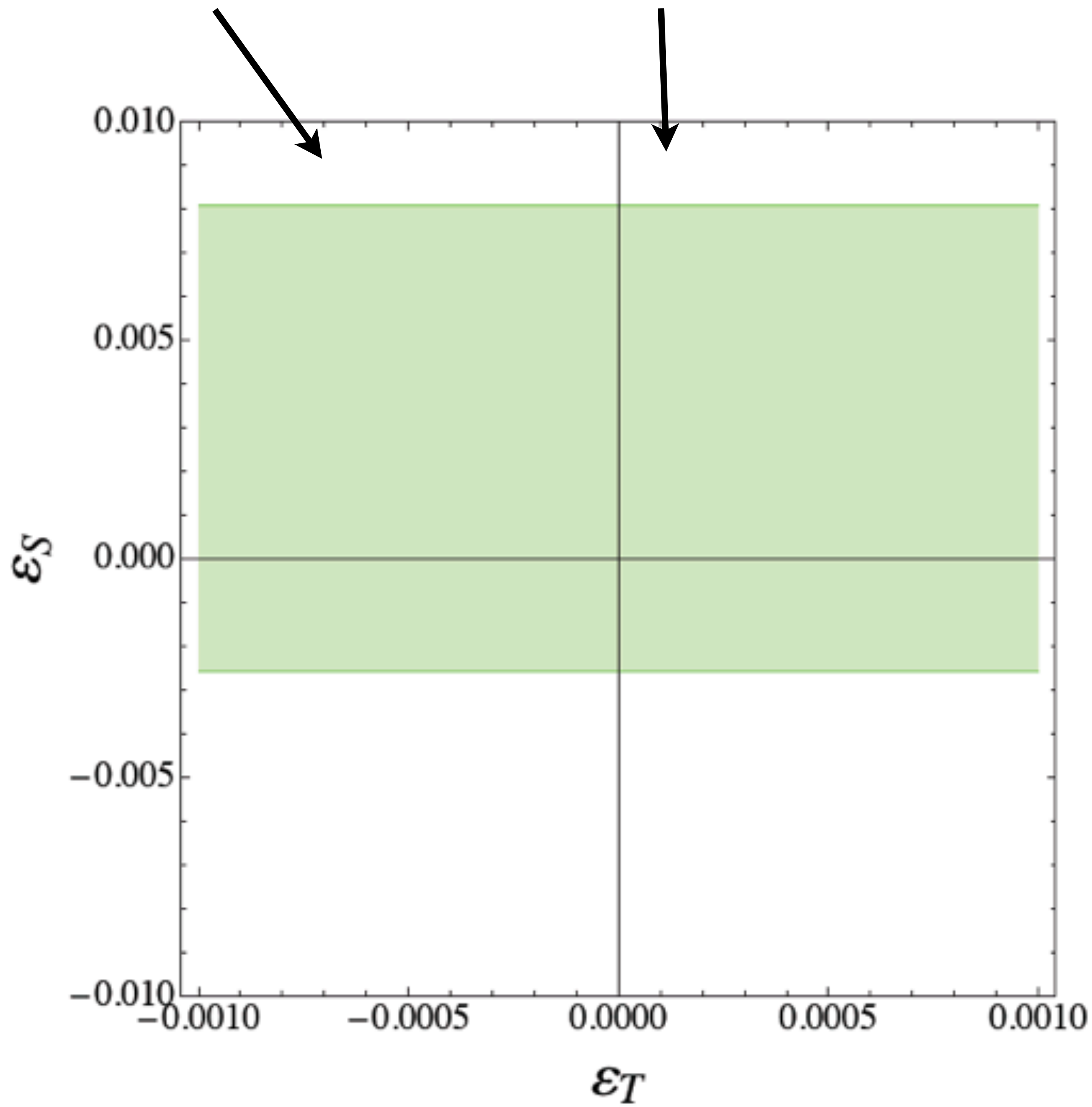
$f_T = 0.24(4) \leftrightarrow$



Mateu-Portoles 07

Constraints on $\varepsilon_{S,T}$

- Current: $0^+ \to 0^+$ (b_F) and $\pi \to e \nu \gamma$ and neutron + nuclear decays



This plot uses

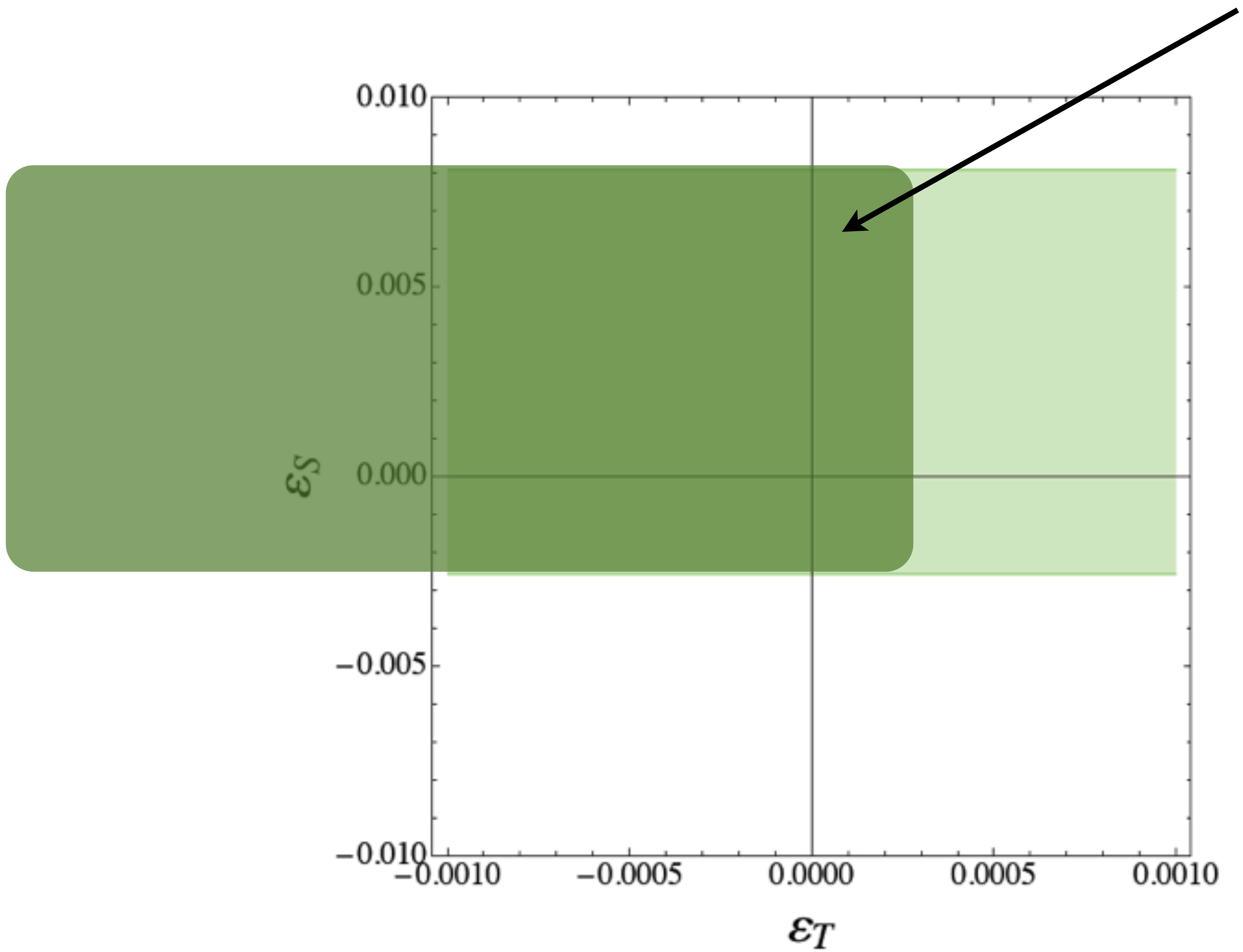
g_S = 0.8 (4)

from LQCD

Bhattacharya, Cirigliano, Cohen, Filipuzzi, Gonzalez-Alonso, Graesser, Gupta, Lin, 2011

Constraints on $\varepsilon_{S,T}$

- Current: $0^+ \to 0^+$ (b_F) and $\pi \to e \nu \gamma$ and neutron + nuclear decays



Wauters-Garcia-Hong
1306.2608

Based on global analysis of nuclear decays & neutron lifetime + beta asymmetry "A"

Constraints on $\varepsilon_{S,T}$

- Current: $0^+ \to 0^+$ (b_F) and $\pi \to e \nu \gamma$ and neutron + nuclear decays
- Future: neutron b, B = B_0 + b_ν m_e/E_e @ 10^{-3}; ^{6}He (b_{GT}) @10^{-3}

Sensitive to different combinations of ε_S and ε_T

$$b_{\rm GT} = -(8\gamma/\lambda)\, g_T\, \epsilon_T$$

$$b = \frac{2}{1+3\lambda^2}\left[g_S\, \epsilon_S - 12\lambda\, g_T\, \epsilon_T\right]$$

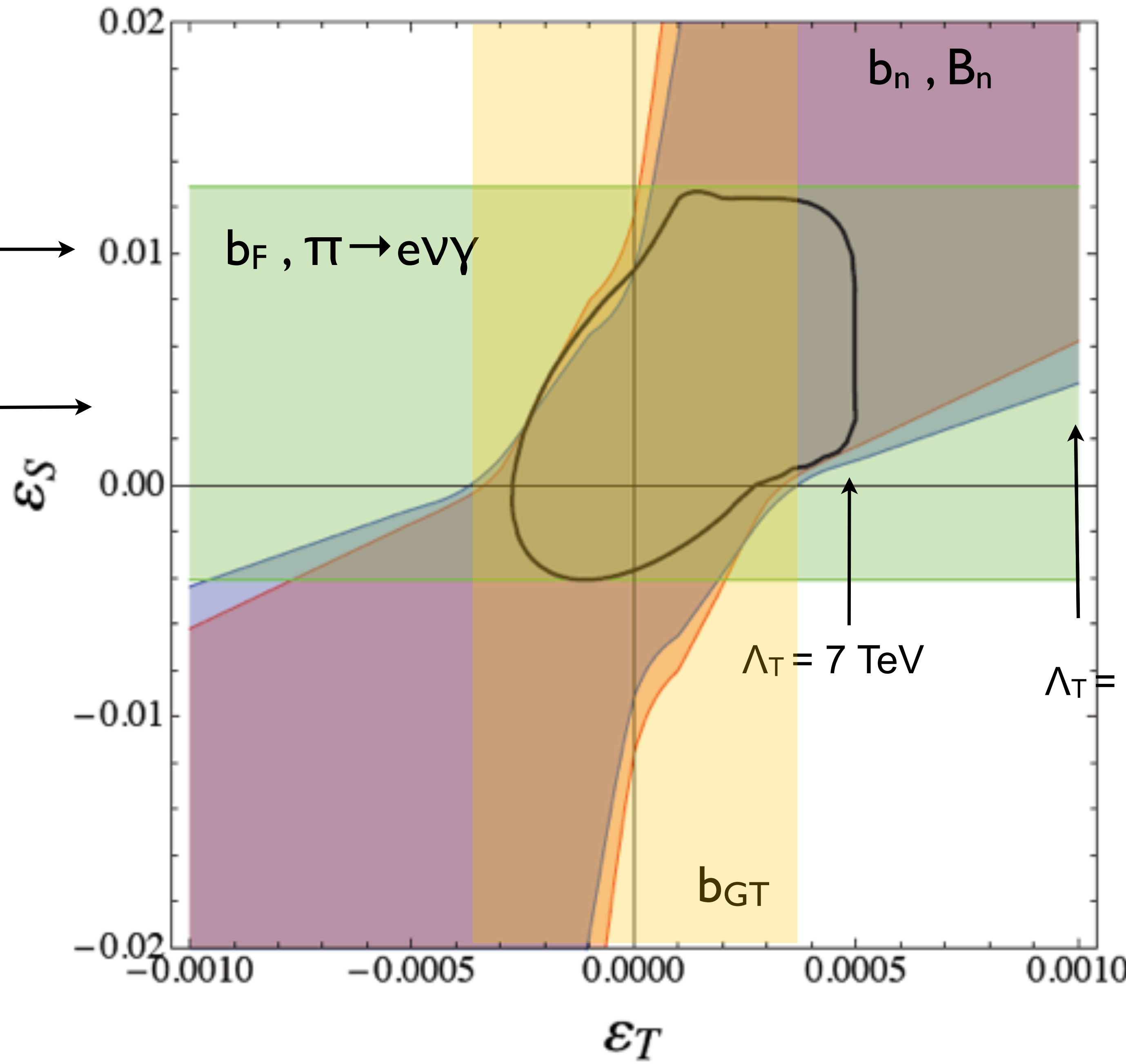
$$b_\nu = \frac{2}{1+3\lambda^2}\left[\lambda g_S\, \epsilon_S - 4(1+2\lambda)\, g_T\, \epsilon_T\right]$$

Constraints on $\varepsilon_{S,T}$

- Current: $0^+ \to 0^+$ (b_F) and $\pi \to e \nu \gamma$
- Future: neutron b, $B = B_0 + b_\nu\, m_e/E_e$ @ 10^{-3}; ^{6}He (b_{GT}) @10^{-3}

Λ_S = 3.2 TeV →

Λ_S = 5 TeV →



Λ_T = 7 TeV

Λ_T = 5 TeV

(90% C.L.)

Quark models:

$0.25 < g_S < 1$

$0.6 < g_T < 2.3$

Adler et al, '75
Herczeg '01

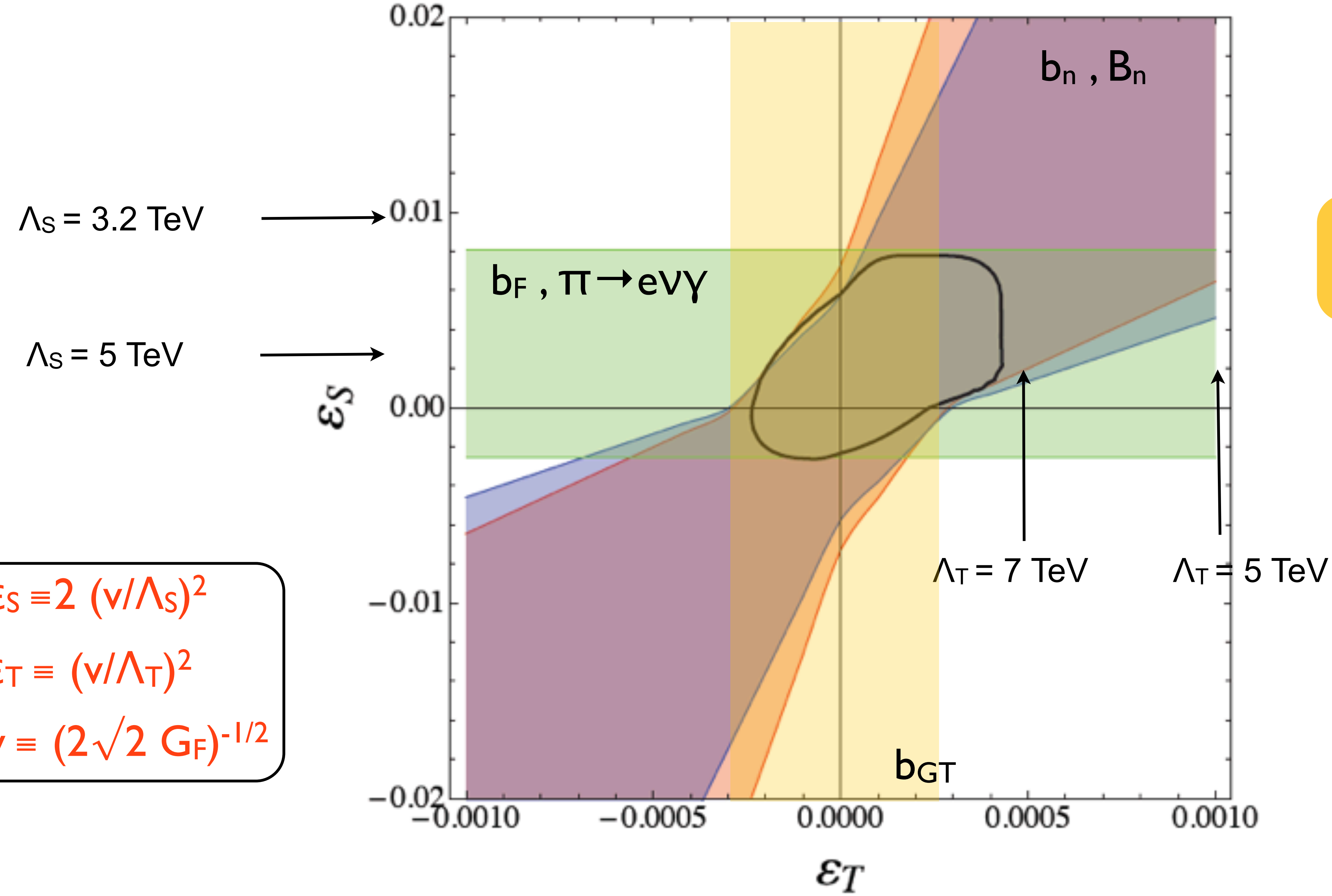
$\varepsilon_S \equiv 2\,(v/\Lambda_S)^2$

$\varepsilon_T \equiv (v/\Lambda_T)^2$

$v \equiv (2\sqrt{2}\, G_F)^{-1/2}$

Constraints on $\varepsilon_{S,T}$

- Current: $0^+ \to 0^+$ (b_F) and $\pi \to e \nu \gamma$
- Future: neutron b, $B = B_0 + b_\nu \, m_e/E_e$ @ 10^{-3}; ^{6}He (b_{GT}) @10^{-3}



(90% C.L.)

Lattice QCD

$g_S = 0.8\,(4)$

$g_T = 1.05(35)$

Bhattacharya, Cirigliano, Cohen, Filipuzzi, Gonzalez-Alonso, Graesser, Gupta, Lin, 2011

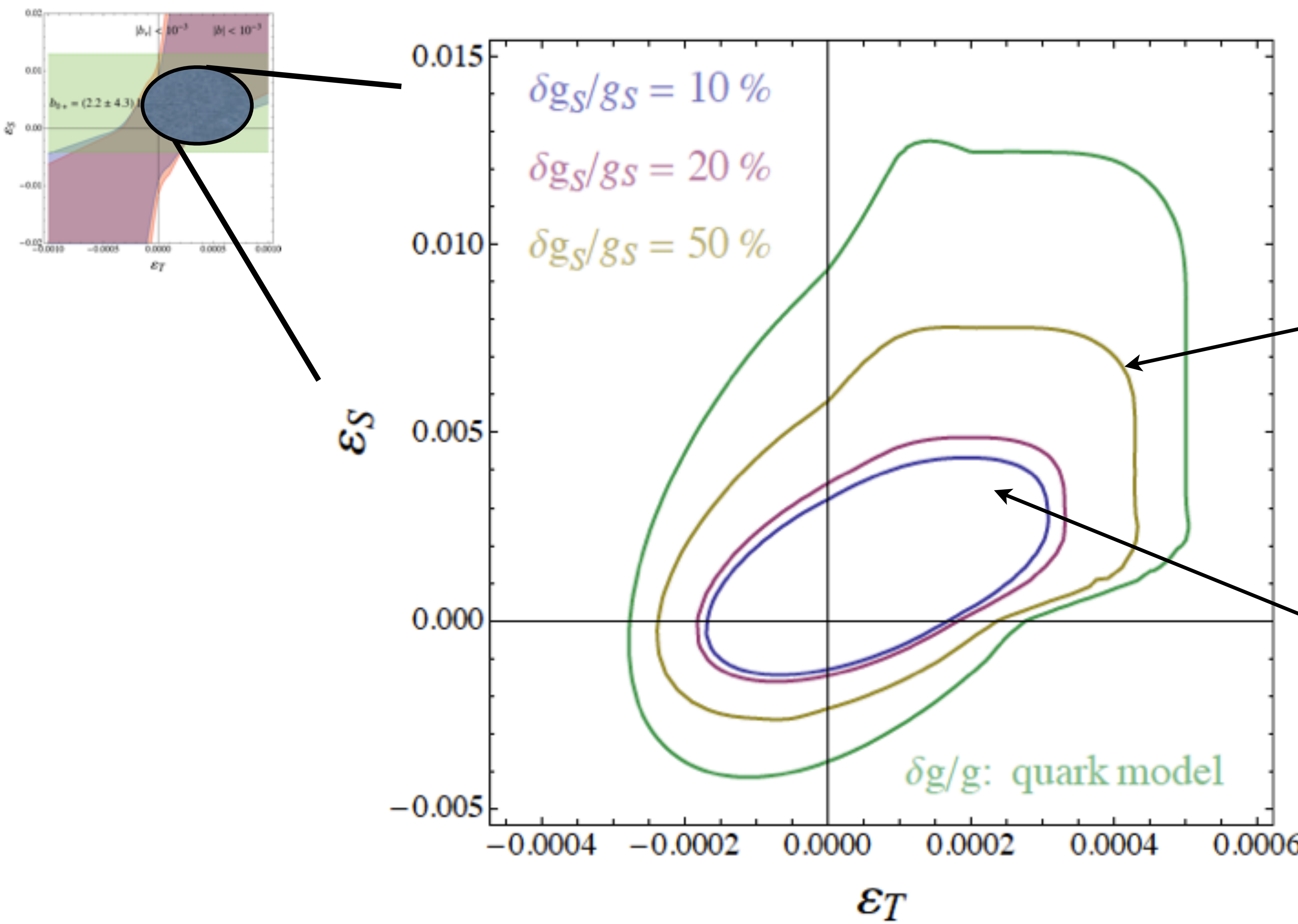
$\varepsilon_S \equiv 2\,(v/\Lambda_S)^2$

$\varepsilon_T \equiv (v/\Lambda_T)^2$

$v \equiv (2\sqrt{2}\,G_F)^{-1/2}$

Impact of QCD uncertainties

- Hadronic uncertainties ($g_{S,T}$) strongly dilute significance of bounds
- Future LQCD calculations will improve constraints



(90% C.L.)

current lattice results

$\delta g_{S,T}/g_{S,T} \sim 20\%$ from LQCD needed to fully exploit experimental advances

Summary of low-E constraints

	$\mathrm{Re}(\epsilon_L)$	$\mathrm{Re}(\epsilon_R)$	$\mathrm{Re}(\epsilon_P)$	$\mathrm{Re}(\epsilon_S)$	$\mathrm{Re}(\epsilon_T)$
β decays	0.05	0.05	0.06	0.8	0.1

$\times 10^{-2}$

$\Gamma(\pi \to e\nu)\,/\Gamma(\pi \to \mu\nu)$

	$\mathrm{Re}(\tilde{\epsilon}_L)$	$\mathrm{Re}(\tilde{\epsilon}_R)$	$\mathrm{Re}(\tilde{\epsilon}_P)$	$\mathrm{Re}(\tilde{\epsilon}_S)$	$\mathrm{Re}(\tilde{\epsilon}_T)$
β decays	6	6	0.03	14	3.0

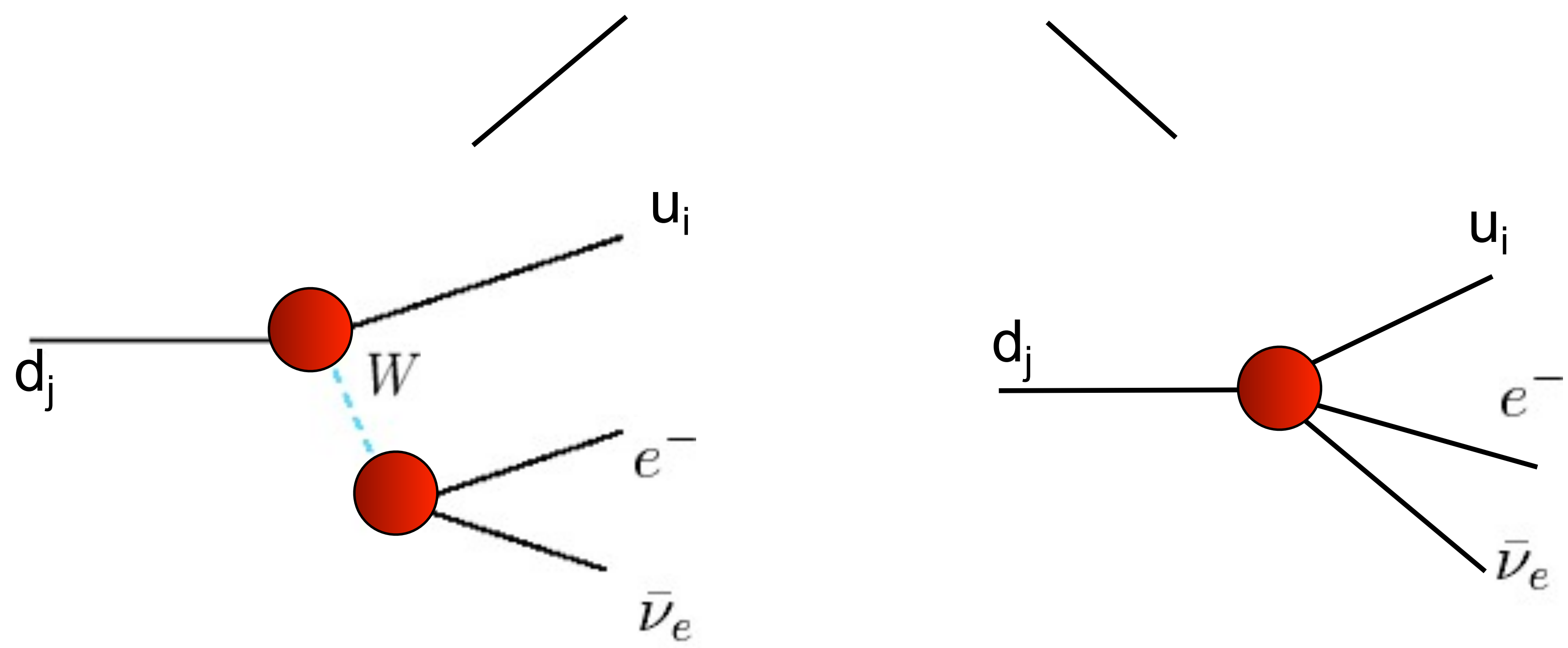
$\times 10^{-2}$

High-energy probes

Constraints from LEP & SLC

- The weak-scale operators that contribute to the ε_α, affect other observables (precision EW + collider)
- Strongest constraints on "L" coupling

$$\epsilon_L = \epsilon_L^{(v)} + \epsilon_L^{(c)}$$



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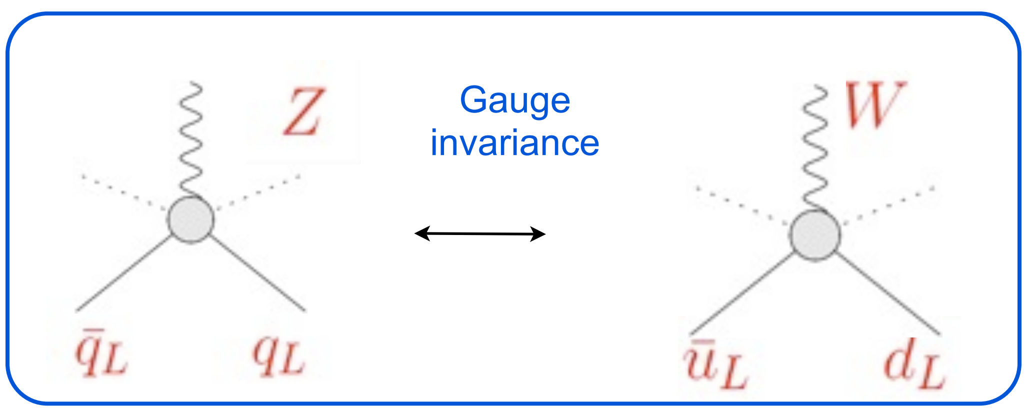
$$|\epsilon_L|_{\text{vertex}} < 5 \times 10^{-4}$$



- Already strong constraints from Z-pole
- CKM is at the same level

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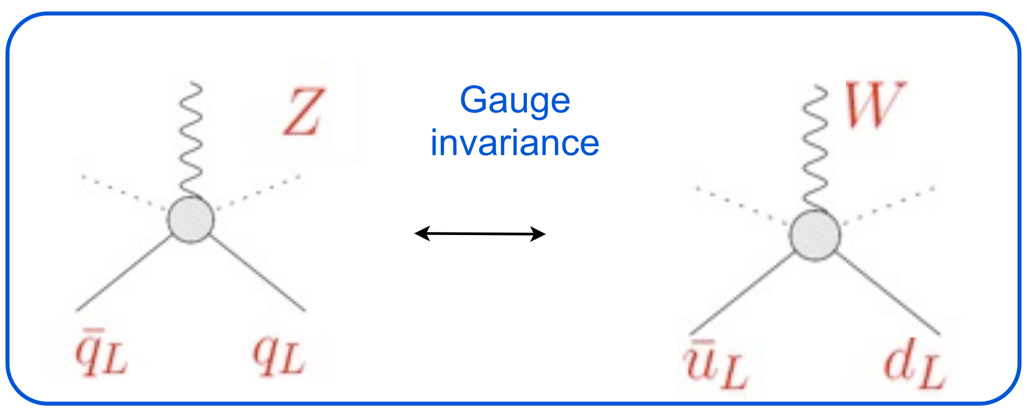
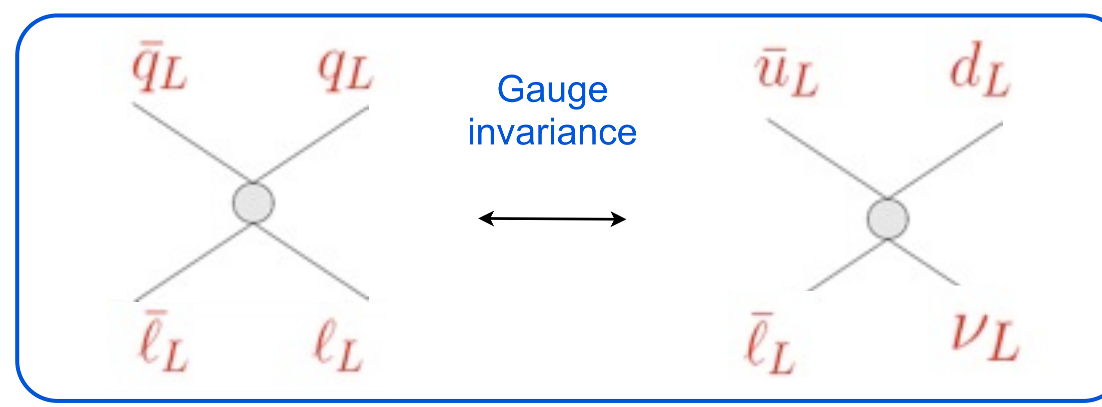


- Already strong constraints from Z-pole
- CKM is at the same level

$$|\epsilon_L|_{4-{\rm fermi}} < 4 \times 10^{-3}$$

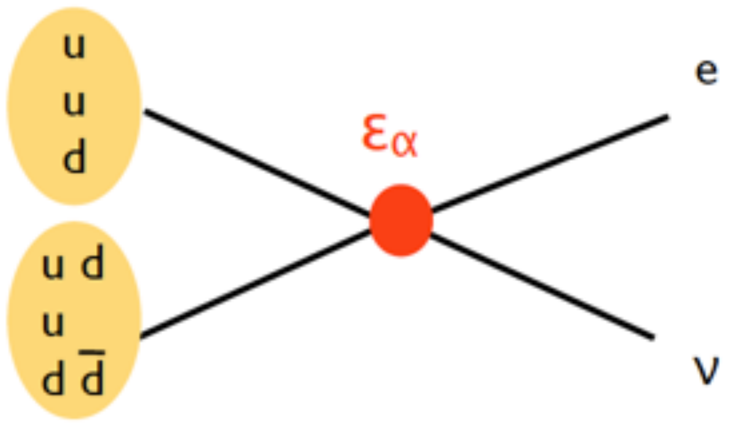


- Constraints from σ_{had} at LEP would allow Δ_{CKM} ~0.01 !!
- CKM "wins" by factor of ~ 10

LHC (I): contact interactions

- If the new physics originates at scales $\Lambda >$ TeV, then can use EFT framework at LHC energies

- The effective couplings ε_α contribute to the process $p\,p \rightarrow e\,\nu + X$



Bhattacharya, Cirigliano, Cohen, Filipuzzi, Gonzalez-Alonso, Graesser, Gupta, Lin, 2011

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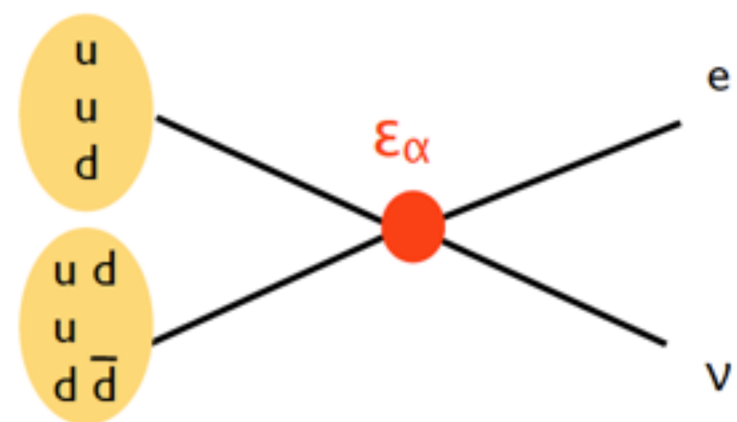
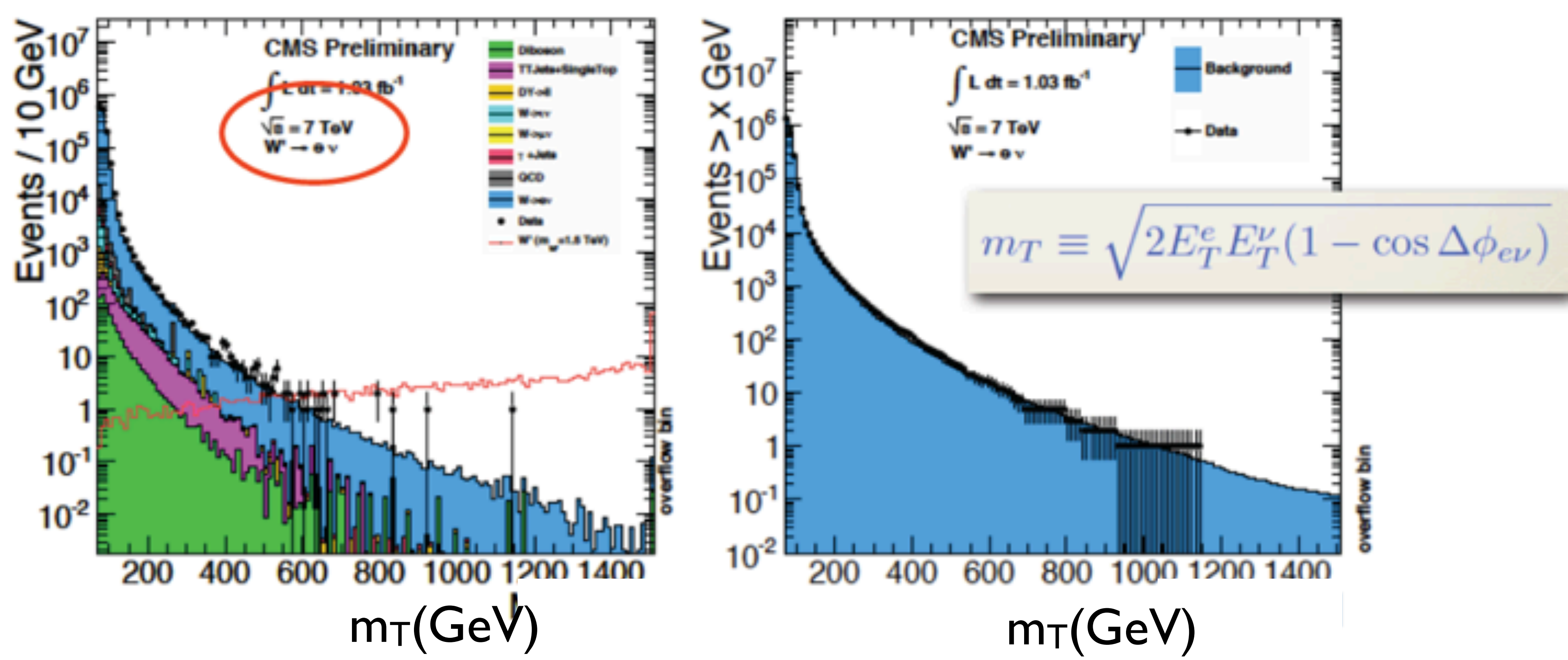


- No excess events in transverse mass distribution: bounds on ε_α

differential

cumulative



VC, Gonzalez-Alonso, Graesser, 2012

- Bounds on the effective scalar and tensor couplings:

$$n_{obs}\,(m_T > m_{T,cut}) = \varepsilon_{eff} \times \mathcal{L} \times (\, \sigma_W + \sigma_S \times |\varepsilon_S|^2 + \sigma_T \times |\varepsilon_T|^2)$$

detection efficiency * geometric acceptance

integrated luminosity

SM contribution

BSM contribution

VC, Gonzalez-Alonso, Graesser, 2012

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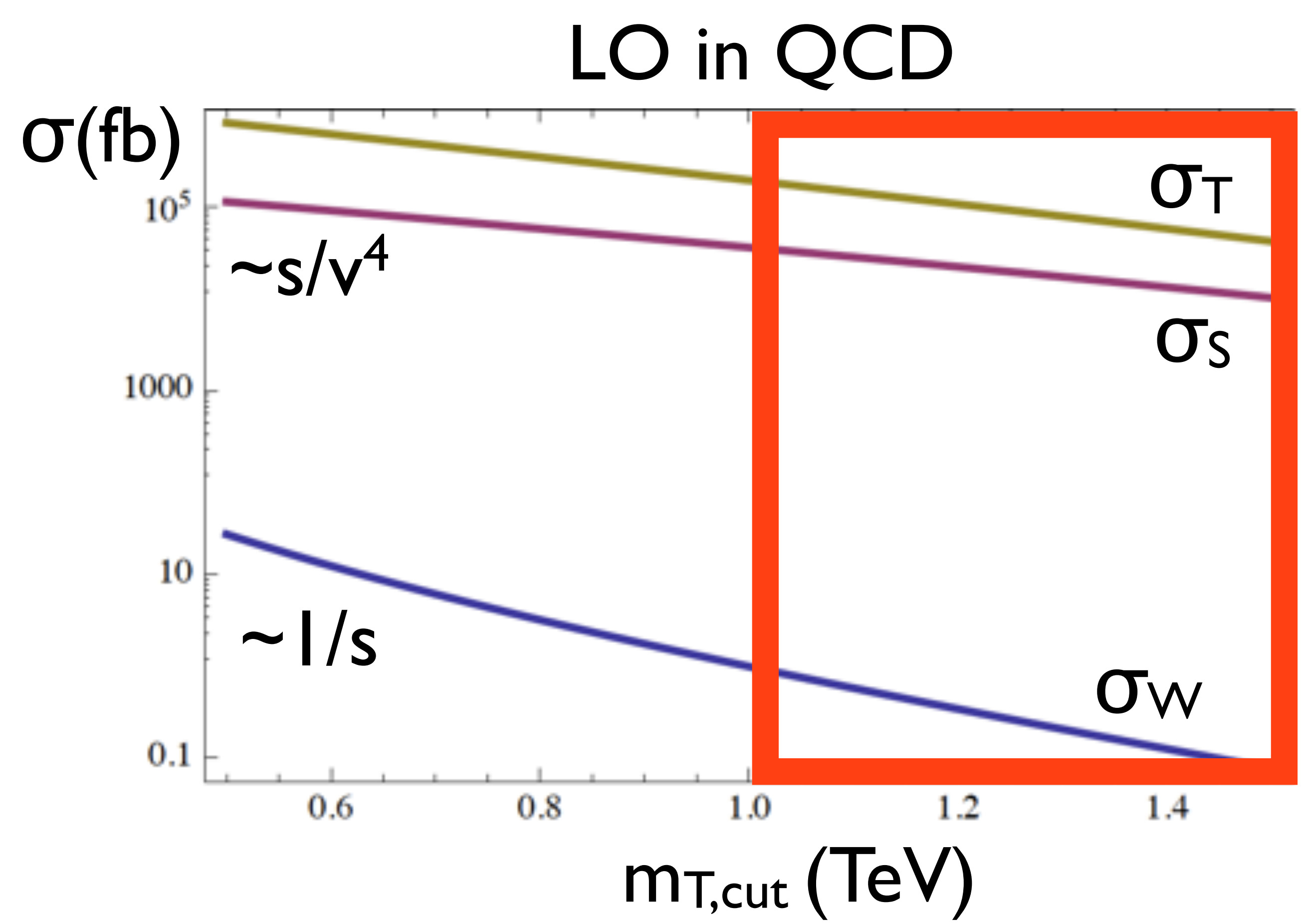
$$n_{obs}\,(m_T > m_{T,cut}) = \varepsilon_{eff} \times \mathcal{L} \times (\,\sigma_W + \sigma_S \times |\varepsilon_S|^2 + \sigma_T \times |\varepsilon_T|^2)$$

- BSM effects $\propto |\varepsilon_{S,T}|^2$, but (i) $\sigma_{S,T} >> \sigma_W$ and (ii) $\sigma_{S,T}$ and σ_W have different behavior in $m_T \Rightarrow$ to suppress bkg, use large $m_{T,cut}$



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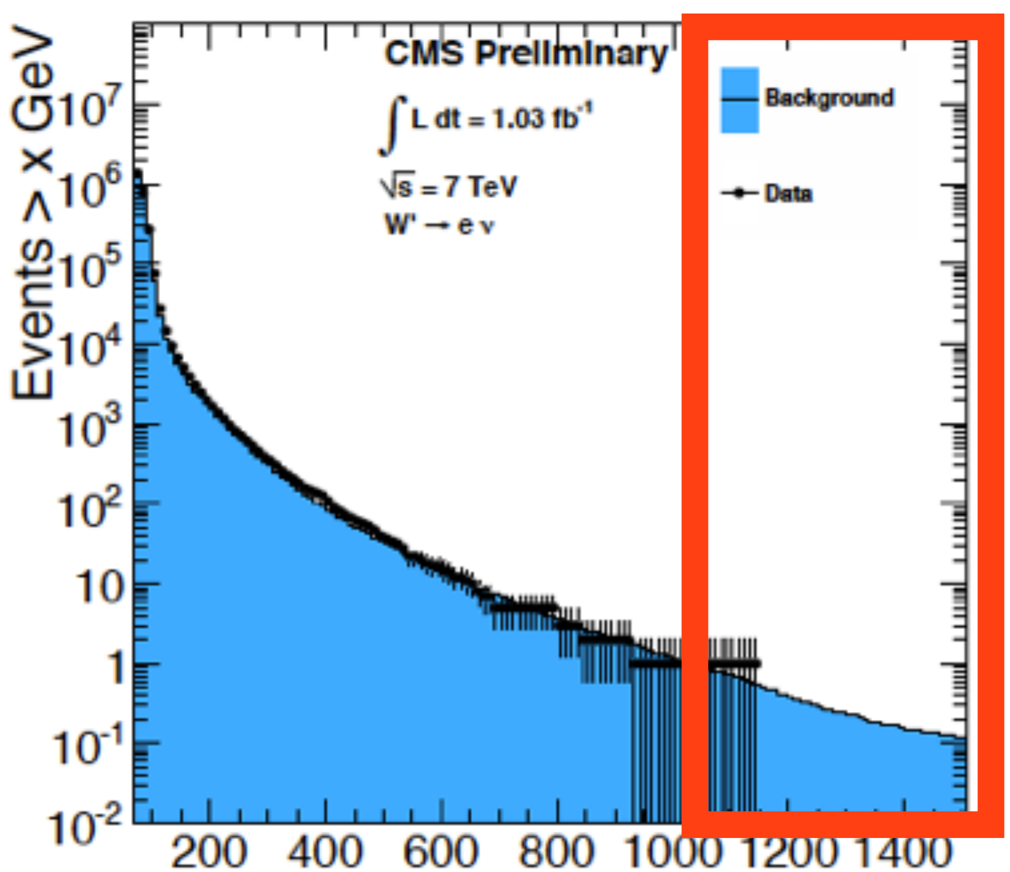
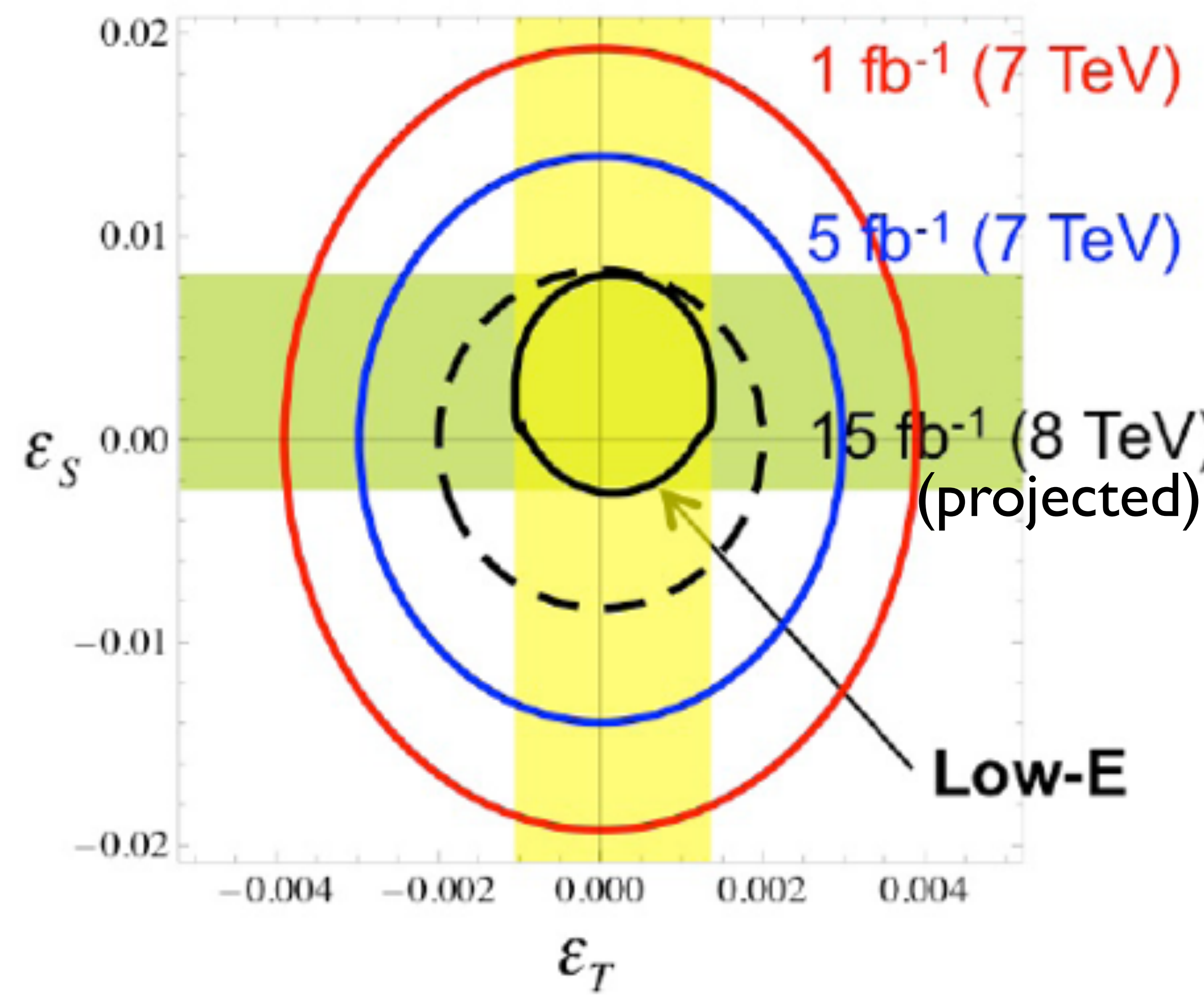


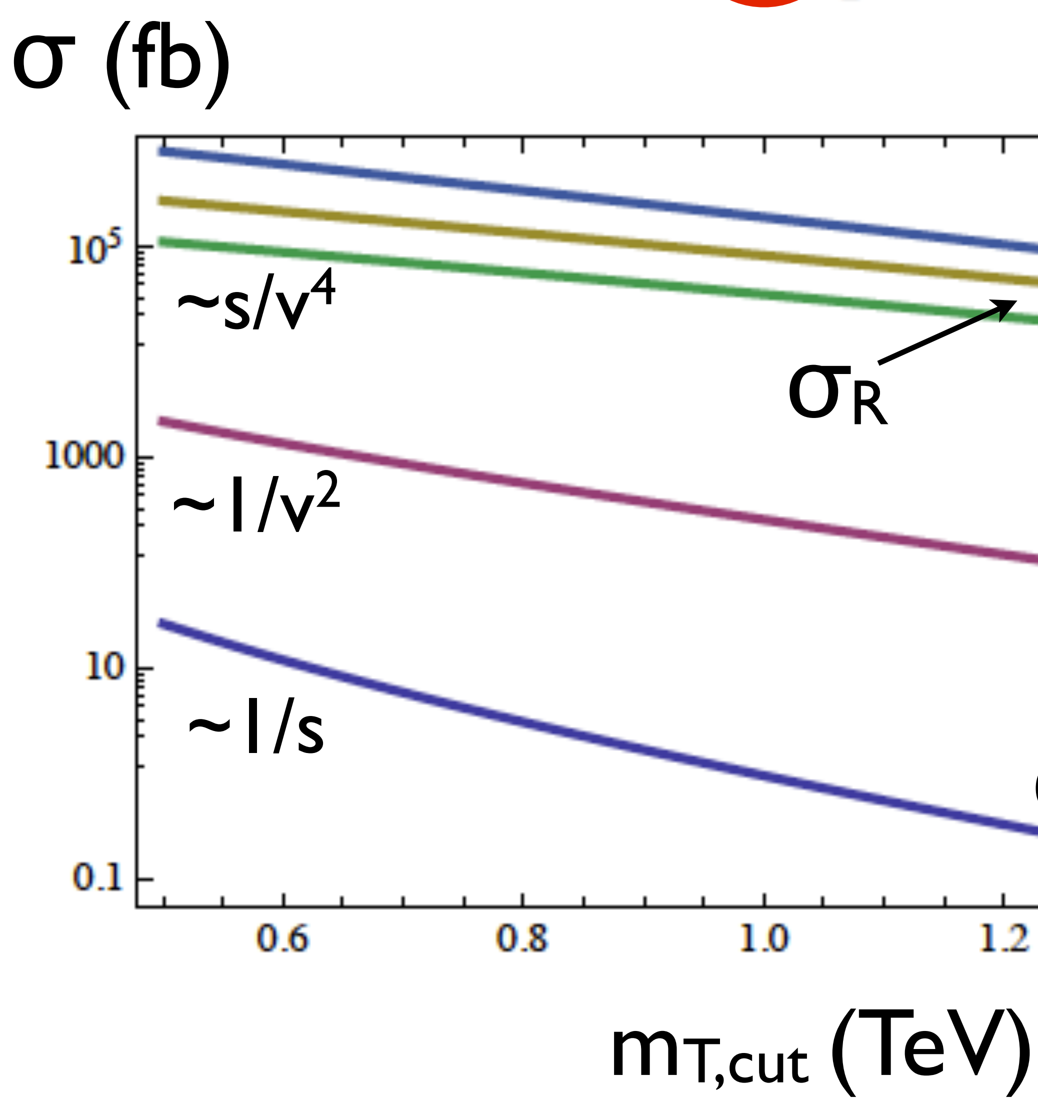
$m_{T,cut}$ (GeV)



VC, Gonzalez-Alonso, Graesser, 2012

- Bounds on all the other effective couplings:

$$\sigma(m_T > \overline{m}_{T,cut}) = \sigma_W \left[(1+\epsilon_L^{(v)})^2 + |\tilde{\epsilon}_L|^2 + |\epsilon_R|^2\right] - 2\sigma_{WL}\, \epsilon_L^{(c)} \left(1+\epsilon_L^{(v)}\right) + \sigma_R \left[|\tilde{\epsilon}_R|^2 + |\epsilon_L^{(c)}|^2\right] + \sigma_S \left[|\epsilon_S|^2 + |\tilde{\epsilon}_S|^2 + |\epsilon_P|^2 + |\tilde{\epsilon}_P|^2\right] + \sigma_T \left[|\epsilon_T|^2 + |\tilde{\epsilon}_T|^2\right],$$

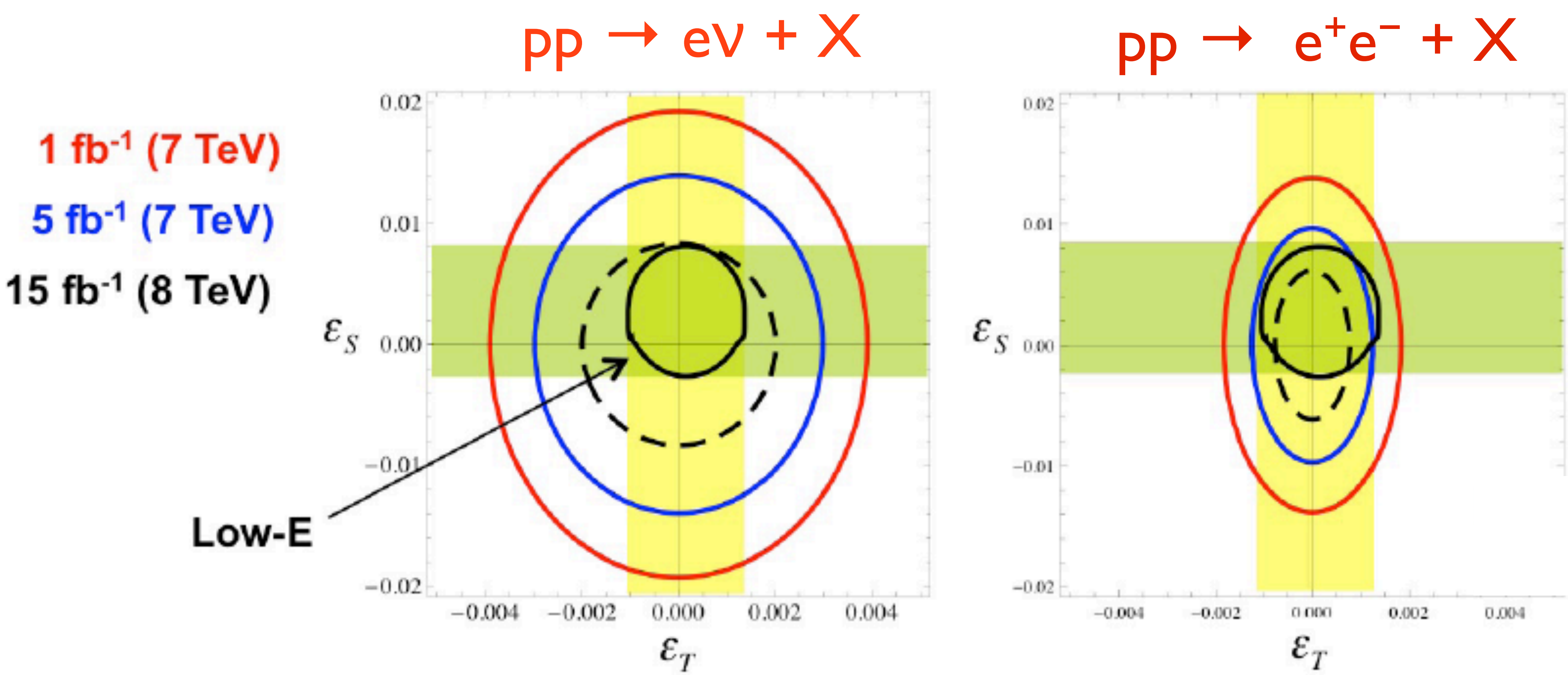


⇒

- Strong bounds on S,T, P couplings with LH ν's
- Strong bounds on S,T,P, R couplings with RH ν's
- Less sensitivity to other couplings

Constraints form pp → e^+e^- + X

- Using SU(2) symmetry, ε_α contribute to pp → e^+e^- + X
- The resulting constraints are slightly stronger than pp → eν + X



VC, Gonzalez-Alonso, Graesser, 2012
VC, Gardner, Holstein 2013

β decays vs LHC

All ε's in $\overline{\text{MS}}$ @ μ = 2 GeV

	$\text{Re}(\epsilon_L)$	$\text{Re}(\epsilon_R)$	$\text{Re}(\epsilon_P)$	$\text{Re}(\epsilon_S)$	$\text{Re}(\epsilon_T)$
β decays	0.05	0.05	0.06	0.8	0.1
LHC ($e\nu$)	$(-0.3, +0.8)$	–	1.3	1.3	0.3
LHC (e^+e^-)	–	–	1.0	1.0	0.1

$\times 10^{-2}$

Unmatched low-energy sensitivity

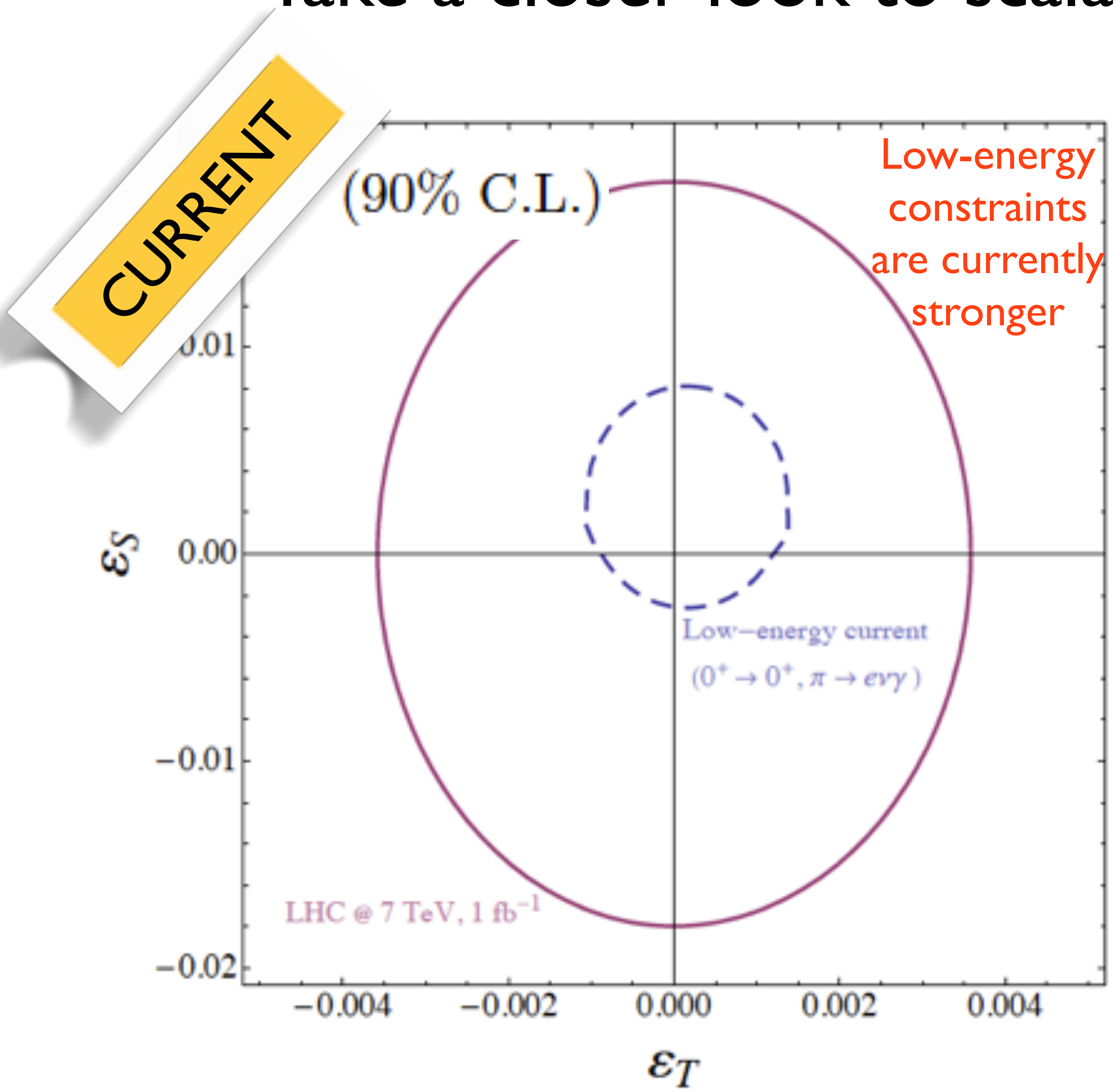
LHC limits close to low-energy. Interesting interplay in the future

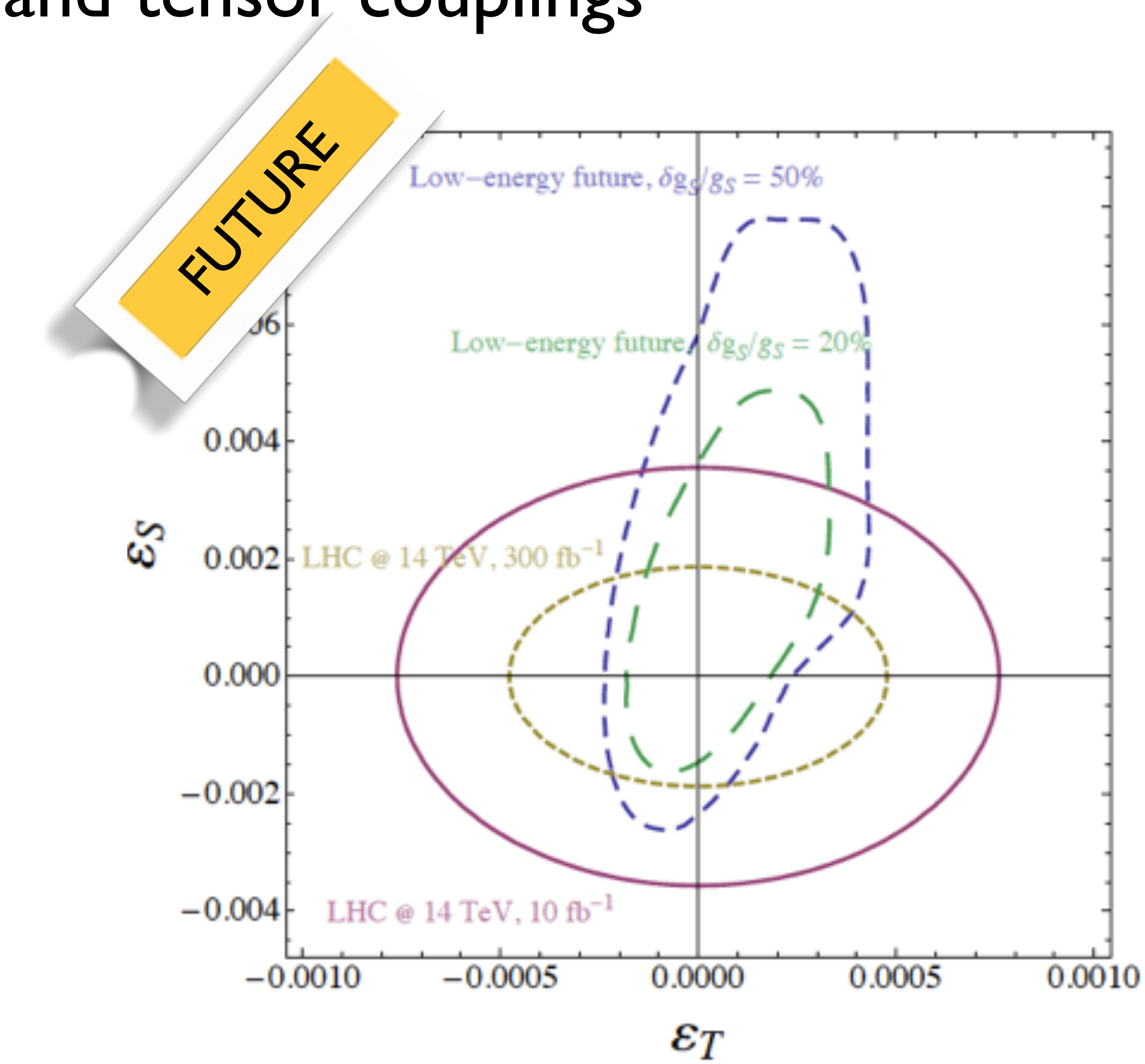
	$\text{Re}(\tilde{\epsilon}_L)$	$\text{Re}(\tilde{\epsilon}_R)$	$\text{Re}(\tilde{\epsilon}_P)$	$\text{Re}(\tilde{\epsilon}_S)$	$\text{Re}(\tilde{\epsilon}_T)$
β decays	6	6	0.03	14	3.0
LHC ($e\nu$)	–	0.5	1.3	1.3	0.3

$\times 10^{-2}$

LHC stronger than low-energy! (except for P,L)

- Take a closer look to scalar and tensor couplings





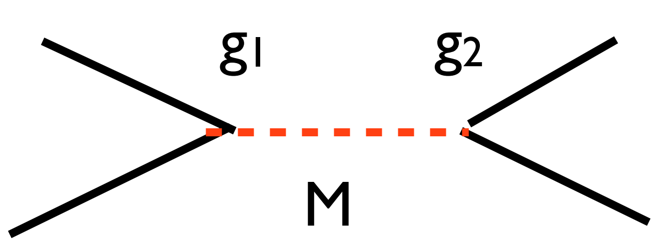
- LHC and b, B at 10^{-3} level will compete in setting strongest bounds on ε_S and ε_T probing effective scales $\Lambda_{S,T} \sim 7$ TeV
- b and B at 10^{-4} level would give unmatched sensitivity

VC, Graesser, Passemar, in progress

LHC (II): beyond contact

- What if new interactions are not "contact" at LHC energy? How are the ε bounds affected?

- Explore classes of models generating $\varepsilon_{S,T}$ at tree-level. Low-energy vs LHC amplitude:



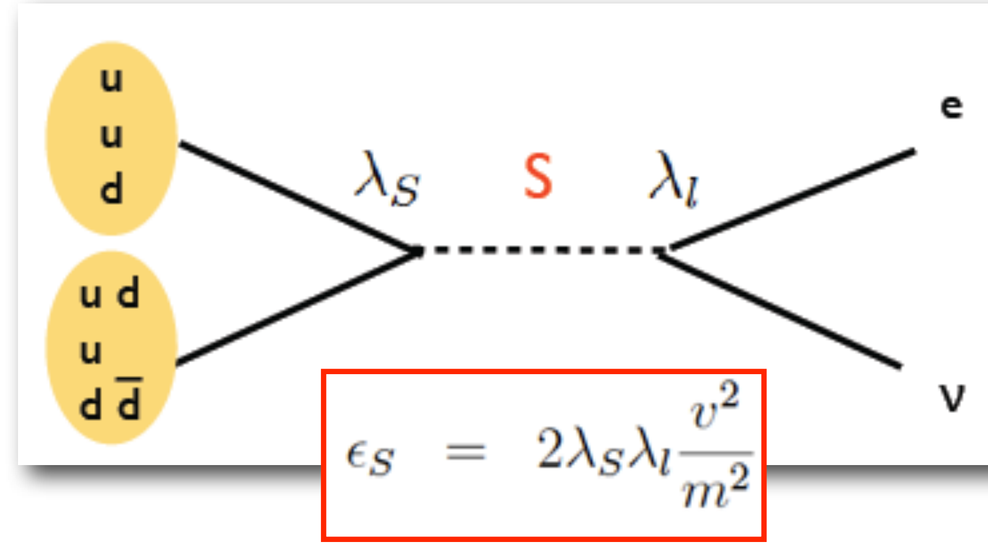
$$A_\beta \sim g_1 g_2/M^2 \equiv \varepsilon$$

$$A_{LHC} \sim \varepsilon\, F[\sqrt{s}/M, \sqrt{s}/\Gamma(\varepsilon)\,]$$

- Study dependence of the ε bounds on the mediator mass M

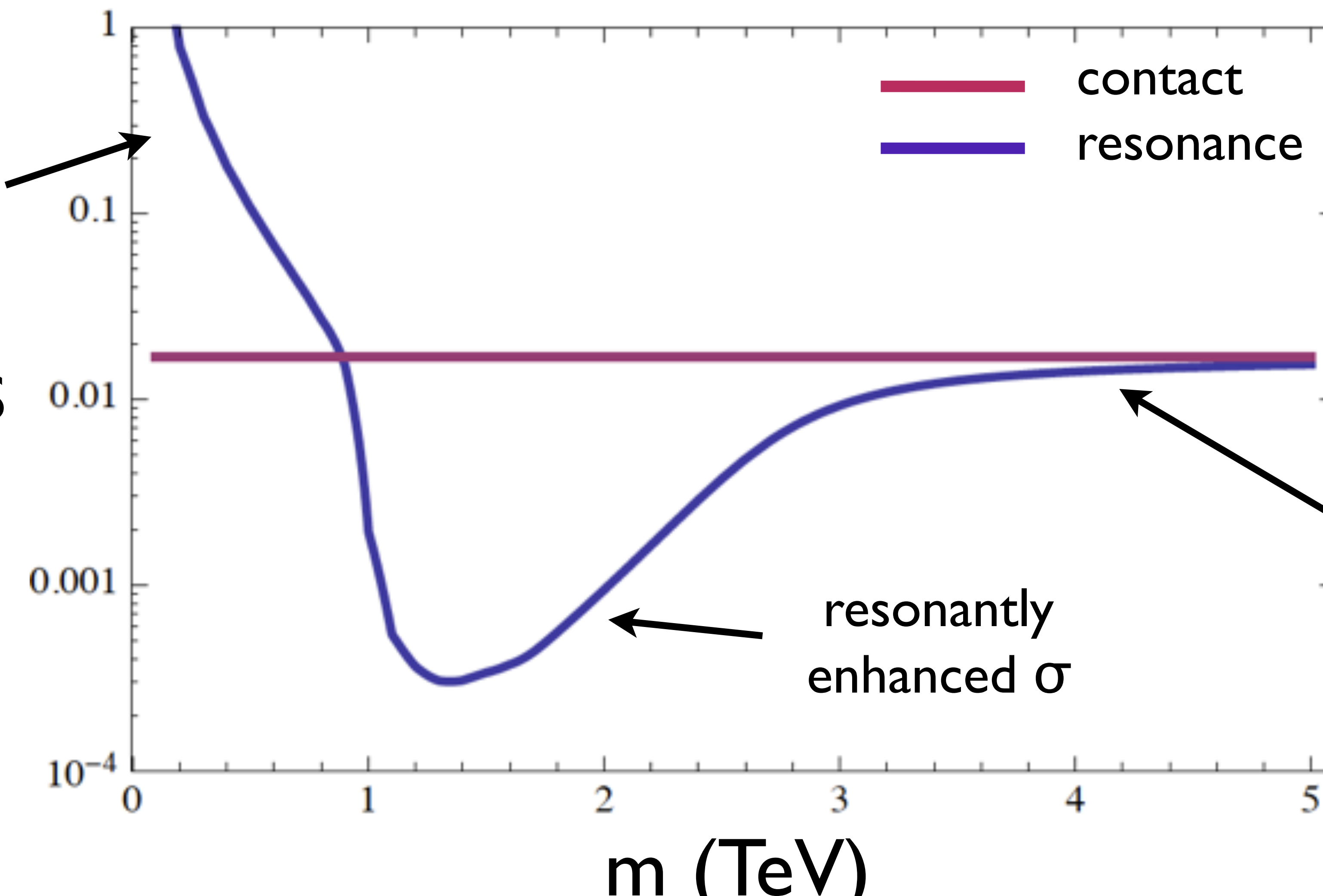
s-channel mediator

- Scalar resonance in s-channel
- Upper bound on ε_S based on $m_{T,cut}$ = 1 TeV



σ suppression due to $m < m_{T,cut}$

Improvable with lower $m_{T,cut}$
But larger SM bkg

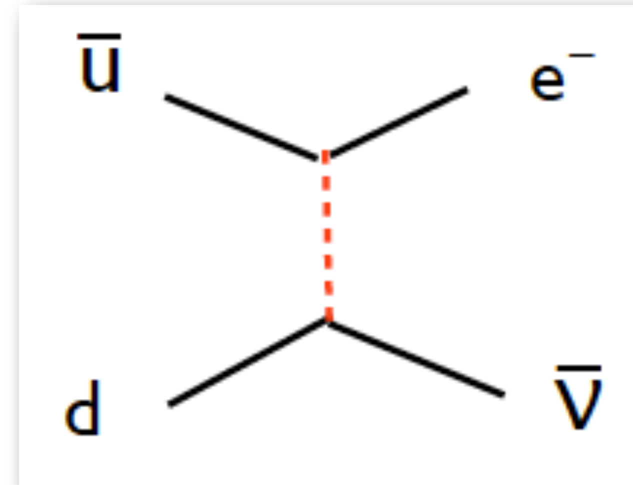


resonantly enhanced σ

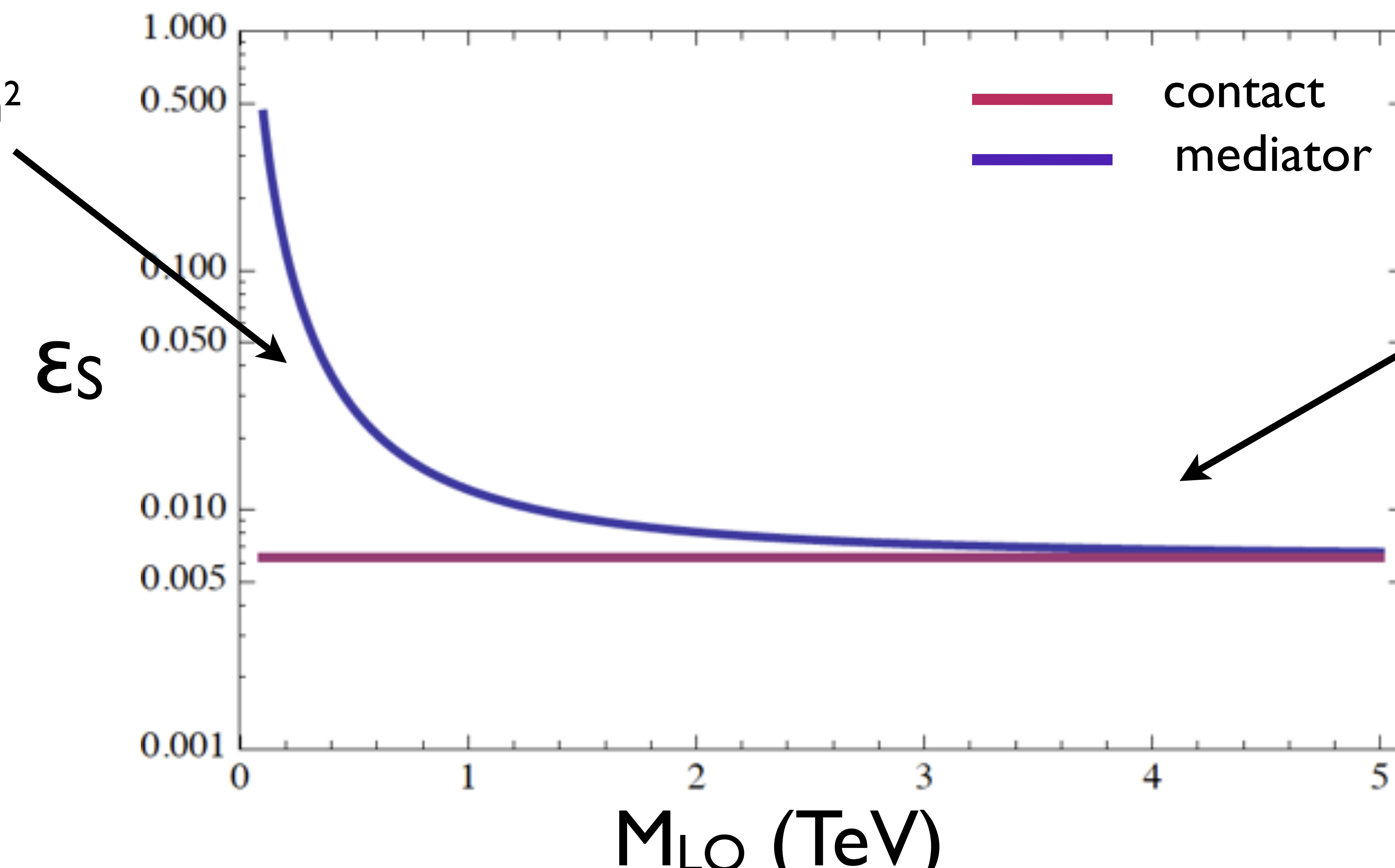
decoupling regime

t-channel mediator

- Scalar leptoquark S_0 (3*,1,1/3)
- $\varepsilon_T = -1/4\ \varepsilon_S = -1/4\ \varepsilon_P$



σ suppression due to 1/(m² - t) vs 1/m²



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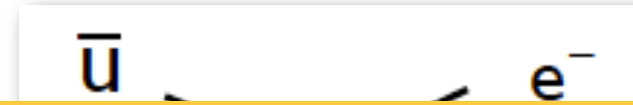
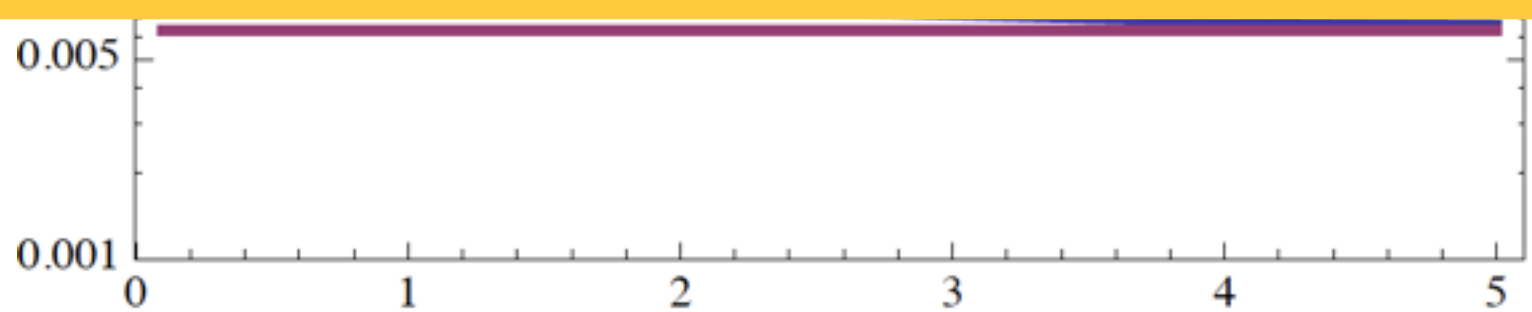


Messages

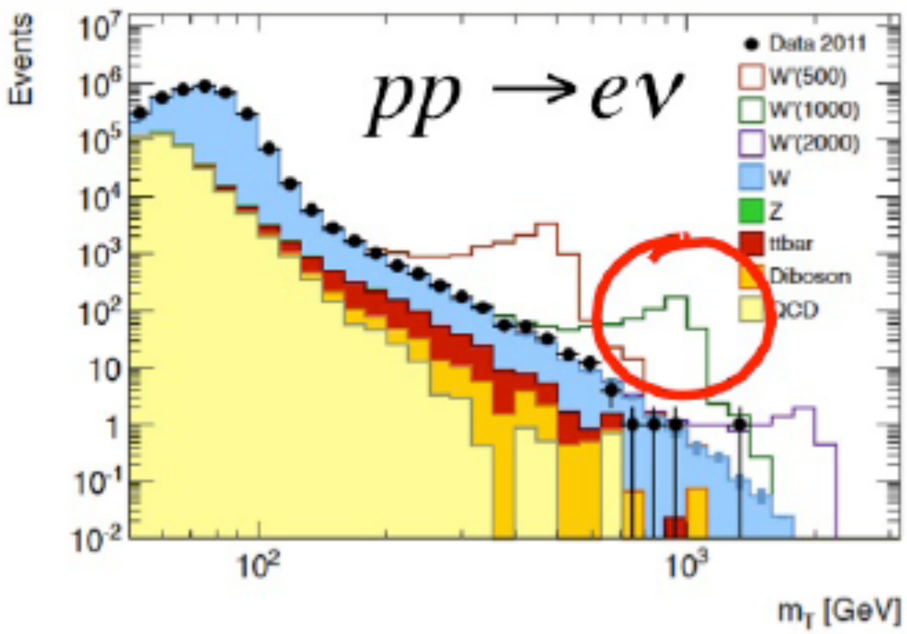
- For mediator mass >1TeV, LHC bounds on ε's based on contact interactions are "conservative": actual bound is stronger for s-channel resonance, comparable for t-channel
- For low mass mediators (m < 0.5 TeV), the LHC bounds on ε's quickly deteriorate: limits based on contact interactions are unreliable

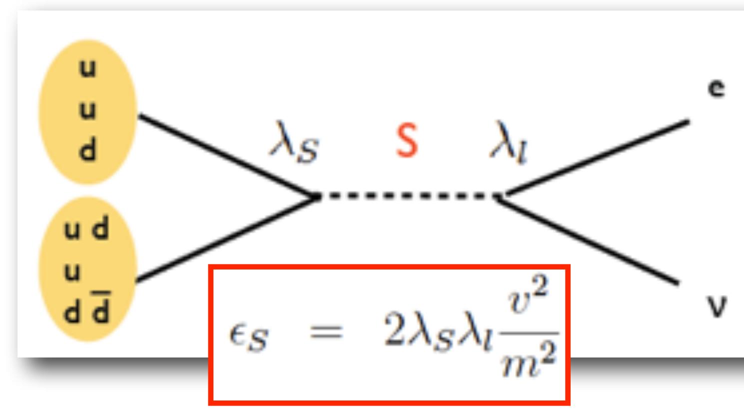


M_{LQ} (TeV)

What if LHC sees something?

- If "bump" in m_T is due to a scalar resonance coupling to $e + \nu_e$



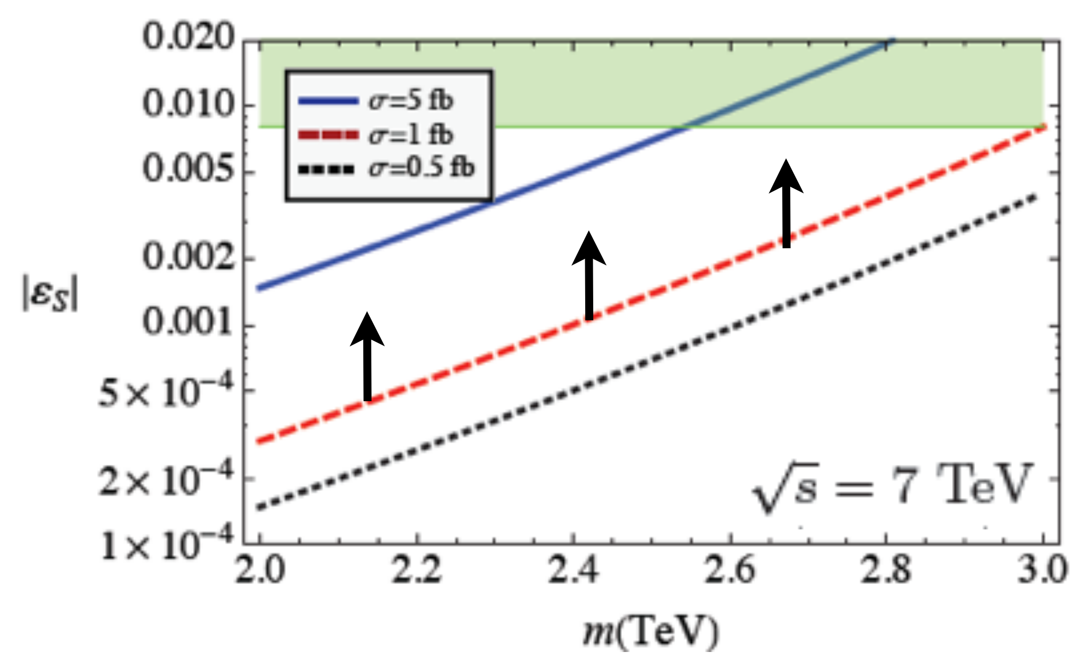


- ...then we a lower bound on ε_S: β-decays provide diagnostic power

$$\sigma \cdot \mathrm{BR} \leq \frac{|V_{ud}|}{12v^2}\frac{\pi}{\sqrt{2N_c}}|\epsilon_S|\tau L(\tau)$$

$$L(\tau) = \int_\tau^1 dx f_q(x) f_q'(\tau/x)/x$$

$$\tau = m^2/s$$



What if LHC sees something?

- If "bump" in m_T is due to a scalar resonance coupling to e + ν_e

Diagnostic power

- Spin of resonance
- Nature of "MET" (is it ν_e?)
- Additional scalars? (suppression of ε_S through interference)

$$\sigma \cdot \mathrm{BR} \;\leq\; \frac{|V_{ud}|}{12 v^2} \frac{\pi}{\sqrt{2N_c}} |\epsilon_S| \tau L(\tau)$$

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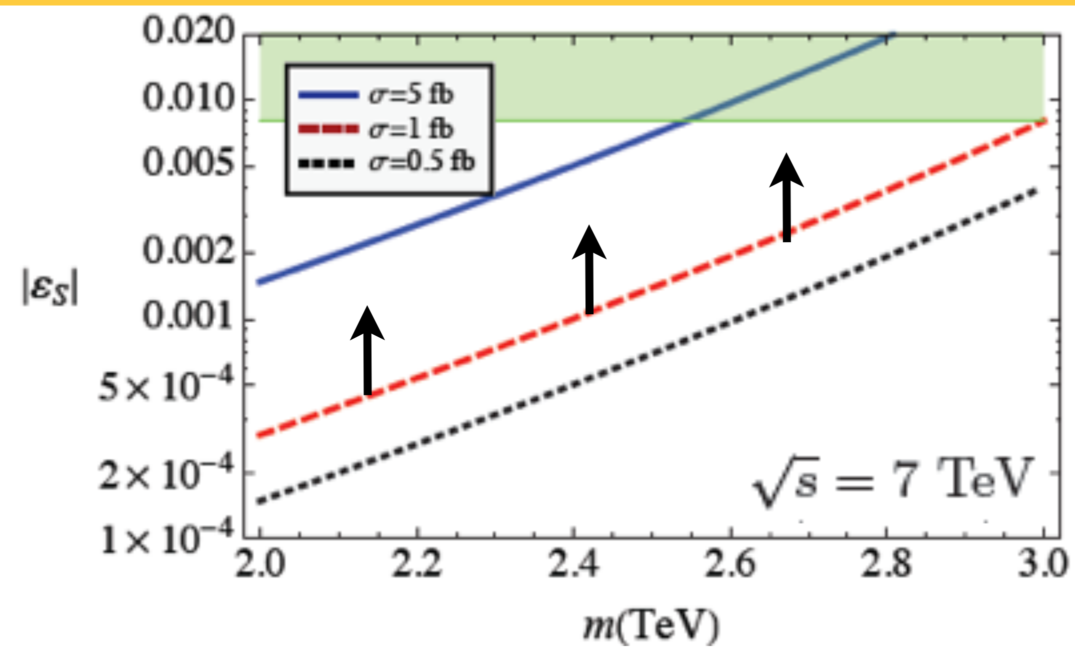

Conclusions

- Precise ($\lesssim$0.1%) beta decays: "broad band" probe of new physics
- If new physics arises above the TeV scale, EFT approach gives model-independent connection between β-decays and HEP
- Positive outlook: for operators involving ν_L, beta decays probe effective scales in the multi-TeV range
  - "Nightmare scenario" (mediators not accessible at the LHC): 0.1%-level β decays can be more sensitive than LHC
  - "Optimistic scenario": β decays provide diagnostic power to reconstruct TeV-scale dynamics seen at the LHC

$$\Downarrow$$

Either way, relevance of beta decays well in the LHC era